Patterns of note onset asynchronies in expressive piano performance

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This paper presents an analysis of the asynchronies among nominally simultaneous notes in ten graduate student pianists' performances of three compositions (Schumann's "Träumerei," Debussy's "La fille aux cheveux de lin," and Chopin's Prelude in D-flat major), each repeated twice and recorded in MIDI format on a Yamaha Disklavier. Note onset times were sensed from hammer motion shortly before hammer-string contact. A pervasive tendency was found for the highest-pitched notes (usually the principal melody) to lead lower-pitched notes, especially those played with the same hand. Inner notes of within-hand chords tended to lag behind outer notes. Strong correlations between average MIDI velocity difference and average lead time were found within each hand, as well as between hands for some of the pianists. Other pianists had a tendency to lead with the left hand, independent of MIDI velocity. These individual differences in between-hand coordination were stable across the three compositions and did not reflect handedness. The results suggest that within-hand asynchronies and melody leads are largely a consequence of dynamic differentiation of voices (i.e., an artifact of hammer travel time), whereas left-hand leads are an individual characteristic and, in part, a deliberate expressive strategy exhibited by some pianists. © *1996 Acoustical Society of America.*

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INTRODUCTION

Notes that are simultaneous in the printed score often are not played synchronously in piano performance. One obvious reason for this is the imperfection of the human motor system, which introduces a certain amount of temporal variability, both between the two hands and among the fingers of each hand. Synchronization of the two hands is a problem for any beginning piano student, and precise synchronization of the fingers in chords remains a technical problem even for advanced pianists. However, onset asynchronies are often larger and/or more systematic than is to be expected on the basis of motor inaccuracy alone, which suggests that additional factors are at work.

Pianists play notes by moving their hands and fingers to depress keys which cause hammers to hit strings which produce tones that reach a listener's ears. Asynchronies may be observed at different stages in this process—at kinematic, mechanical, acoustic, and perceptual levels. *Finger-key contact asynchronies* (kinematic level) have rarely been studied, as this requires video recordings or sensors on the key surfaces. *Key-bed contact asynchronies* (kinematic/mechanical levels) were analyzed in a recent study by Palmer (in press). Most performance studies have used photoelectric systems that register the movement of the piano hammers shortly before their collision with the strings, so that *hammer impact asynchronies* (mechanical level) may be observed. If a MIDI system is used to acquire these data, the registered times are known as "note onsets," so the term *note onset asynchronies* may be used in referring to MIDI data.[1] At the acoustic level, *tone onset asynchronies* may be observed, though they are difficult to determine accurately from a composite waveform. Tone onset asynchronies are virtually identical with hammer impact asynchronies, but they will differ from key-bed contact asynchronies, especially at low key/hammer velocities where the key travel time exceeds the hammer travel time (Askenfelt and Jansson, 1990). Piano tones may have perceptual onsets that lag behind their acoustic onsets by several tens of milliseconds, depending on their amplitude rise time (Schütte, 1978; Vos and Rasch, 1981; Gordon, 1987). Since rise time increases with pitch (Repp, 1995a), *perceptual onset asynchronies* may differ from tone onset or hammer impact asynchronies. Moreover, they are subject to limits of auditory sensitivity such as the temporal order threshold (Hirsh, 1959).

If a pianist aims for synchrony of finger-key contacts, then a source of systematic but unintended asynchrony at subsequent levels is the *velocity artifact*. When different keys are depressed simultaneously with different forces, the keys having a higher velocity will reach the key bed earlier and will also make their hammers reach the strings earlier to produce louder tones. Consequently, the asynchrony measured at mechanical or acoustic levels will increase monotonically with the difference in key or hammer velocities (or sound levels). A pianist may counteract the velocity artifact by striking the keys asynchronously, aiming instead for synchrony of key-bed contacts or for perceptual synchrony of tone onsets. To what extent pianists adopt such strategies is unknown, but the velocity artifact must be reckoned with in any investigation of asynchronies, particularly among notes played by the same hand, as noted by Ortmann (1962, p. 358). In addition, pianists may introduce asynchronies intentionally or habitually to achieve special expressive effects.

In one of the earliest objective analyses of piano performance, Hartmann (1932) compared two famous artists' piano roll recordings of the first movement of Beethoven's Sonata in c-sharp minor, op. 27, No. 2, and observed that in

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both performances the left hand almost always preceded the right hand at the beginnings of measures. One of the two pianists also tended to play the lower note of left-hand octaves before the higher note, whereas he tended to play notes in the right hand (soprano melody and alto accompaniment) simultaneously. The absolute magnitude of the asynchronies was not reported.[2] Left-hand leads are unlikely to be a velocity artifact, as the right hand usually plays at a higher dynamic level than the left hand. Presumably, they are employed to anticipate the harmony and/or lend accent to a melody note by delaying its onset, a strategy that is conventionalized in notated *arpeggi* and grace notes.

Henderson (1936), in another early study, examined two pianists' performances of the central chorale-like section in Chopin's Nocturne in *g* minor, op. 15, No. 3, recorded with the help of the "piano camera" in Seashore's laboratory (Henderson *et al.*, 1936). In this passage the left hand plays single bass notes while the right hand plays mostly 3-note chords. Henderson found an average "chord spread" (the difference between the earliest and latest onsets within a chord) of 20 ms for one pianist and of 70 ms for the other. The latter tended to play the bass notes before the chord.[3] Both pianists consistently played the melody note (the soprano voice) before the other notes in the right hand, which may well represent the velocity artifact. Henderson pointed out that the melody was about 5 dB more intense than the accompaniment but seemed to regard the melody leads as an independent expressive strategy.

Still the most thorough study of asynchronies in the literature is Vernon's (1936) analysis of four famous pianists' performances of eight pieces or sonata movements, preserved on Duo-art rolls. Unfortunately, there are some measurement artifacts in his data. One of these, a tendency to substitute zero for small asynchronies, was mentioned by Vernon himself. However, his frequency histograms of chord spreads show a much higher incidence of zero values than one would expect on these grounds alone: The percentage of perfectly synchronous chords per performance ranges from 44% to 92%, which seems implausibly high. Vernon noted a tendency for right-hand melody notes to be played in advance of other right-hand notes, but not in advance of left-hand notes. Individual pianists differed in the frequency and magnitude of chord spreads and in their tendency to lead with the left hand. That tendency seemed to accompany (or be the cause of) large asynchronies. Pianists who used large asynchronies purposefully also seemed to be more consistent across repetitions of the same musical material, probably due to the increase in systematic variance.

Vernon proposed five "explanatory principles" for chord spreads: (1) difficulties in synchronization (e.g., in chords with many notes, or when the two hands have different rhythms); (2) tempo changes (e.g., during slow passages or *ritardandi*, or while playing *rubato* in one hand against a steady beat in the other hand, or during *accelerandi* when the melody may run ahead of the accompaniment); (3) highlighting of melody notes (especially in close or bass-heavy chords, also for contrapuntal reasons); (4) conveying of an accent or a climax; (5) avoidance of abruptness (e.g., at the beginnings and ends of phrases, in *legato* passages, at points of large pitch jumps or modulation). He found support for some of these principles in his data, especially (2) and (3), but not for (5). With regard to (3), he mentioned that "in close chords the melody must come first or be louder to have any clarity. Making it louder may also make it earlier." (p. 322). This indicates some awareness of the velocity artifact.[4]

Rasch (1979) proposed a quantitative measure of the amount of asynchrony in a whole performance: The root mean square of the standard deviations of the onset differences among all pairs of voices. He applied this measure in an acoustic analysis of ensemble performances and obtained values between 30 and 50 ms, depending on the music. He found that melody instruments tend to lead, while middle voices tend to lag, though by rather small average amounts. Like Vernon before him, he also observed that (absolute) asynchronies decreased as tempo increased.

Hammer impact asynchronies were examined by Shaffer (1981) in his studies of piano performance from a motor control perspective. In one pianist's rendition of Chopin's Nouvelle Etude No. 1, he found that the right hand tended to lag on the first beat but to lead on the second beat and elsewhere. He inferred from this that the two hands were operating on different time scales, which is consistent with Vernon's second principle. Shaffer also noted a break in the cumulative distribution of asynchronies; he attributed values below 40 ms to random variation and longer values (melody leads) to "voice singing." However, since the dynamics were stronger for the right hand than for the left, at least the shorter melody leads may have represented the velocity artifact. The correlation between the asynchronies in two successive performances by the same pianist was 0.63 (Shaffer, 1984).

More recently, Palmer (1989) has studied note onset asynchronies in performances recorded on an electronic keyboard in MIDI format. (On an electronic instrument, key-bed contact asynchronies are identical with tone onset asynchronies.) Palmer used Rasch's (1979) index of global asynchrony to characterize six pianists' playing of the first 8 bars of Mozart's Sonata in A major, K.331. She found asynchrony values between 13 and 23 ms, as well as a tendency for the melody to lead the other voices by about 20 ms, on the average. Both asynchronies and melody leads were substantially reduced when the pianists were instructed to play "unmusically," which suggested to Palmer that melody leads were used deliberately for expressive purposes. She did investigate whether melody leads were a consequence of playing melody notes louder but found significant correlations between MIDI velocity and temporal onset differences for only two of six pianists. Palmer also examined the reliability of asynchrony patterns across repeated performances of the same music. Five of her six pianists showed significant but only moderately sized correlations, ranging from 0.54 to 0.61. Thus only about one third of the variance seemed to be systematic. In a second study, Palmer (1989) did not find a consistent melody lead in eight pianists' performances of the initial 16 bars of Brahms's Intermezzo in E-flat major, op. 117, No. 1, probably because the melody is in an inner voice most of the time. However, the melody did tend to lead on the first beat of each bar. Asynchronies were again reduced

in "unmusical" playing, and four of the eight pianists showed a significant correlation between melody leads and velocity differences.

Palmer's most recent study (in press) focused entirely on melody leads in performances recorded from a computer-monitored Bösendorfer grand piano that registered key-bed contacts. Six pianists performed the first 27 bars of Chopin's Prelude in D-flat major, op. 28, No. 15.[5] Average melody leads ranged from 20 to 40 ms, except for one student pianist who showed negligible leads. The lead times were reduced in deliberately "mechanical" performances, though not by very much. They were larger in metrically strong (on-beat) than in metrically weak (off-beat) positions, and one experienced pianist showed large left-hand leads at phrase beginnings. There were no significant correlations of asynchronies with MIDI velocity differences. In a second experiment, ten pianists gave repeated performances of part of Beethoven's Bagatelle in G major, op. 126, No. 1, which they had not played before. Average melody leads ranged from 10 to 20 ms and, for student pianists, increased as a function of practice, approaching the somewhat longer leads of expert pianists. Melody leads were most pronounced on the downbeat, and they were much reduced in "mechanical" performances. Only four of the ten pianists showed correlations indicative of a velocity artifact. In a third experiment, one pianist was instructed to emphasize either the upper (right-hand) or the lower (left-hand) voice in the initial bars of Beethoven's Sonata in E major, op. 109. When the upper voice was in focus, it led the other voices by 54 ms, on the average, but that lead was reduced to 25 ms when the lower voice was in focus. When the latter strategy was intentionally exaggerated, the lower voice began to lead. Of course, there were corresponding differences in dynamic balance, and within the unexaggerated conditions there were significant correlations between velocity differences and asynchronies. Finally, Palmer also showed that musical listeners can identify the voice intended to be in focus when presented with musical excerpts in which the note onsets in one or the other voice are advanced by means of computer editing. However, the effect was rather small and present only for listeners who were pianists, whereas dynamic differences provided a much stronger cue to voice emphasis.

Palmer's results have been described in so much detail because she advocates the view that melody leads are an expressive strategy that is largely independent of dynamic differentiation. It is difficult to be convinced of this, however, given the intermittent correlations between dynamics and onset timing in her data. It is possible that a velocity artifact was present but obscured by random timing variability and a relatively small number of observations. Many of her findings—the reduction of asynchronies in "unmusical" playing, the changes in asynchrony with voice emphasis, the difference between expert and student pianists—could have been due to differences in dynamic voice differentiation that entailed changes in relative onset times. Moreover, Palmer did not clearly distinguish between within-hand and between-hand asynchronies, and between individual voices within each hand. The velocity artifact is likely to be present more strongly among the fingers of the same hand than between hands.

The purpose of the present study was to re-examine some of the issues surrounding asynchronies in a set of expressive performances by graduate student pianists, with special attention to individual differences. A tendency for the left hand to lead the right hand is often observed in pianists of an older generation, and it is sometimes considered a mannerism (cf. footnote 3). Will it be encountered in the present sample of young pianists? Are melody leads as common as Palmer's data suggest? What is the relationship between asynchronies and velocity differences within and between hands? These and other questions can be addressed more effectively with the help of a substantial MIDI data base. Such a data base was recently compiled by the author and forms the basis of the following analyses.

I. METHOD

A. The music

The purpose of collecting the present MIDI data was to study aspects of expressive piano performance. Therefore, pieces were selected that were expressive in character but technically relatively undemanding. They all had a moderate to slow tempo and required *legato* articulation and pedaling throughout. They were: "Träumerei" (No. 7 of "Kinderszenen," op. 15) by Robert Schumann; "La fille aux cheveux de lin" (No. 8 of the Preludes, Book I) by Claude Debussy; and Prelude in D-flat major (No. 15 of the 24 Preludes, op. 28) by Frédéric Chopin.[6] These pieces were selected in part because they were likely to be familiar to all pianists, at least from listening.

Space limitations prohibit reproduction of the music here. It would be helpful if the reader had the scores available, but this is not essential.[7] Occasionally, specific positions in the scores will be referred to by using the convention "bar-beat-subdivision"; thus, "15-3-2" refers to the second note in the third beat in bar 15.

B. The pianists

Ten pianists (P1,P2.....P10) participated in the study as paid volunteers. Nine of them were graduate students of piano performance at the Yale School of Music; three were third-year (artist's diploma) students, one was in her second year, and five were in their first year. The tenth pianist was about to enter the graduate program. Their age range was 21 to 29, and they had started to play the piano between the ages of 4 and 8. Seven were female, three male.

C. Procedure

The pianists were informed of the chosen repertoire and were sent copies of the music prior to the recording session. The session took place in a room housing an upright Yamaha MX100A Disklavier connected to a Macintosh computer. The pianist was asked to rehearse the music at the Yamaha for an hour. Subsequently, the pieces were recorded in whichever order the pianist preferred, and then they were repeated twice in the same order. If something went seriously

wrong in a performance, it was repeated immediately. One pianist, P4, was able to record only two performances of each piece; all others recorded three, as planned. At the end of the recording session, the pianist filled out a questionnaire and was paid $50.

The questionnaire asked the pianists, among other things, how well they knew each of the pieces. Schumann's "Träumerei" had been previously studied by three pianists (P5,P7,P8) and played informally by two; the rest knew it well from listening only. Debussy's "La fille aux cheveux de lin" had been studied by three pianists (P5,P7,P9), played informally by three, and heard repeatedly by four. Chopin's Prelude in D-flat major had been studied by four (P1,P6,P8,P9), informally played by three, and heard by three. The pianists were also asked to indicate how satisfied they were with their performances, choosing from the categories "best effort," "good effort," "average," "below average," and "poor." The distributions of responses were as follows: 0, 4, 5, 1, 0 for Schumann, 0, 6, 4, 0, 0 for Debussy, and 0, 3, 4, 3, 0 for Chopin. Even though most performances were not of recital quality, due to the minimal preparation, they were all fluent and expressive.

D. Data analysis

The Yamaha Disklavier registers a "note onset" when a hammer passes a sensor located 1.5 mm from the strings. Thus this study deals with hammer impact times, which are virtually equivalent to acoustic tone onsets. The onset times were recorded with a temporal resolution of 5–6 ms.[8]

The MIDI data were imported as text files into a spreadsheet program, where the note onsets were filtered out and the highest note in each chord was labeled with reference to a numerical (MIDI pitch) transcription of the score. In a second stage, the onset time of this highest note was duplicated next to the onset time of each lower note in the same chord. In the course of that laborious process, wrong pitches were identified and corrected, omitted notes were inserted (but not given an onset time), and added notes were removed. (For an error analysis, see Repp, in press.) Finally, individual note asynchronies (lag times) were computed by subtracting the onset time of the highest note from that of each lower note in the same chord. Thus a positive asynchrony indicates that a note lagged behind the highest note, whereas a negative asynchrony indicates that it preceded the highest note.[9] In general, the asynchronies were unimodally and fairly symmetrically distributed within a performance, so that they could be characterized in terms of means and standard deviations. In the process of calculating these statistics, extreme outliers (more than four standard deviations from the mean) were identified and removed. While some of these outliers represented timing errors, the majority were merely exaggerations of systematic tendencies observed in the bulk of the data, as described below.

E. The velocity artifact

In order to be able to gauge whether a pattern of asynchronies could have arisen from the velocity artifact, it would be good to know how hammer travel time increases with MIDI velocity. The author had an opportunity to measure this relationship on a Yamaha Disklavier Mark II baby grand piano. Disklavier software normally includes a "prelay" function that compensates for the velocity artifact by delaying MIDI input by 500 ms and then activating the key solenoids earlier for soft notes than for loud notes.[10] This function was in effect on the upright Disklavier used for the recordings, but—for unknown reasons—it was not working on the baby grand piano that became available later, resulting rhythmically distorted MIDI playback. To measure the magnitude of the distortion, two series of simple MIDI sequences were constructed, each sequence consisting of two notes (C_4 and E_4) alternating five times, with nominal inter-onset intervals of 500 ms. In one series, C_4 had a fixed MIDI velocity of 60, while the MIDI velocity of E_4 ranged from 30 to 100 in steps of 10. In the other series, the roles of C_4 and E_4 were reversed. The sequences were played back on the Disklavier, and an acoustic recording was made of the radiated sound with a microphone placed close to the open lid of the piano. The recordings were subsequently digitized, and the relative onsets of successive tones were measured in the waveform. The measurements were averaged over the five repetitions and across the two tone combinations.

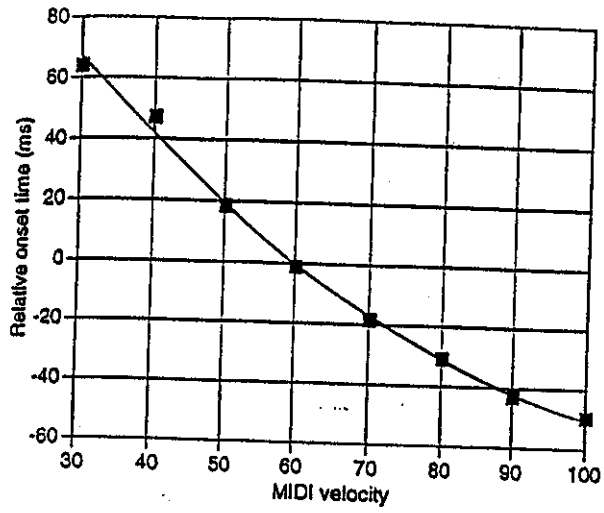

FIG. 1. Onset time (relative to a note with a MIDI velocity of 60) as a function of MIDI velocity. A quadratic function has been fitted to the data points.

The results are shown in Fig. 1. It can be seen that relative onset time decreased as a negatively accelerated (quadratic) function of MIDI velocity. Between the softest and the loudest note, there was an onset time difference of about 110 ms.[11] At lower dynamic levels, relative onset time changed by about 2 ms per velocity unit, whereas at higher levels this was reduced to about 1 ms. Although these relationships may differ slightly from instrument to instrument and perhaps also across pitch registers, Fig. 1 provides a general idea of the magnitude of the velocity artifact.[12]

II. RESULTS

The results will be presented by composition, in order of increasing length and difficulty (Schumann, Debussy,

Chopin). These pieces represent different kinds of textures that make different demands on within- and between-hand coordination.

A. Schumann's "Träumerei"

This composition has a very regular structure comprising eight four-bar phrases. Phrases 1 and 2 are repeated as phrases 3 and 4; phrase 5, related to phrase 2, is transposed to become phrase 6; phrase 7 repeats phrase 1, and phrase 8 is a modified and abbreviated version of phrase 2. The writing is partially polyphonic in four parts.

1. Outliers

In bar 22-2-1, there is a large *fermata* chord which cannot be spanned by small hands. Only two pianists (both male) played it synchronously as notated, two played the bass note early, two played the left hand *arpeggio*, and four played both hands *arpeggio*. Two pianists also arpeggiated a subsequent left-hand chord (23-1-1) in one or two performances. In addition, one pianist (P9) consistently played the left-hand note early in the three-note chord in bar 2-2-1 and its six similar recurrences. Five additional large asynchronies apparently represented timing errors, as each occurred only once.

2. Asynchrony distributions

"Träumerei" can be divided fairly consistently into four voices (soprano, alto, tenor, bass), with some subsidiary notes. The soprano is the leading voice most of the time, but occasionally other voices compete or take over the principal melody (bars 7–8, 10–12, 14–16). All soprano (S) and alto (A) notes are played by the right hand, and all tenor (T) and bass (B) notes by the left hand. Occasional "extra" notes are considered subsidiary to the principal voices: they are always lower in pitch. All simultaneities have soprano notes as their highest notes, with the exception of one true four-note chord occurring six times (bar 1-2-1 and analogous positions), whose highest note was attributed to the alto voice.[13]

Mean asynchronies and standard deviations were computed separately for the four voices in each of the three (or two) individual performances of each pianist and then averaged across performances. Between-performance differences in these global statistics were generally small. The results are displayed in Fig. 2, with the zero line representing the highest-pitch reference. The soprano asynchronies represent only the relative onsets of a small number of subsidiary soprano notes (S+), such as E_4 at 3-4-2 and F_4 at 4-1-1. It can be seen that the ten pianists were quite consistent in that their lower right-hand notes (S+, A) generally lagged behind the soprano voice, with the alto voice lagging more than S+ for five of the pianists, and less for one (P3). There were large individual differences, however, in the relationship of the two hands. Four pianists (P1, P5, P7, P8) showed a slight tendency for the left hand (T, B) to lag even more than the alto notes in the right hand. Two pianists (P6, P9) showed no such tendency, but their left hand still had positive average lag times. Three pianists (P2, P4, P10) showed a tendency for the left-hand notes to approximately coincide with the soprano voice, and thus to lead the lower notes in the right hand. Finally, P3 even showed a tendency for the left hand to precede the right-hand melody. The lag times for the two left-hand voices, tenor and bass, did not differ much in most cases, though P2, P3, and P10 showed a tendency to lead with the bass, P5 the opposite.

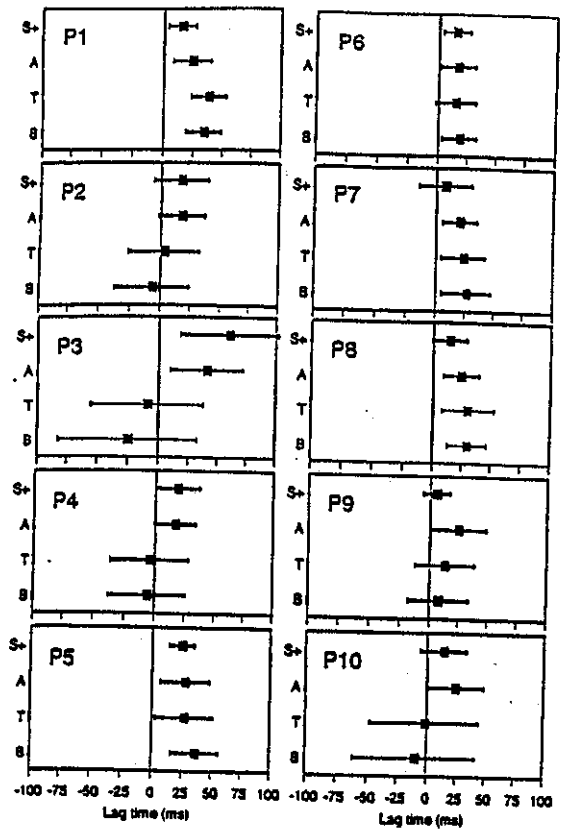

FIG. 2. Average lag times relative to the highest note in each chord plus/minus one standard deviation for the individual voices in Schumann's "Träumerei."

3. Reliabilities

The differences in mean asynchrony among the different voices (or hands) were quite similar in each pianist's three (or two) performances. The next question of interest was whether there were, in addition, reliable patterns of asynchrony variation *within* each voice. P3 and P10, who showed the largest standard deviations and the strongest tendency to lead with the left hand, also committed the largest number of pitch errors (Repp, in press). Thus it seemed possible that these pianists were merely careless, in which case their asynchronies should show a fairly random distribution. To address this issue, correlations were computed between pairs of performances (1-2, 1-3, 2-3) for each voice separately as well as overall, and each triplet of correlations was then averaged. The results are shown in Table I.

The correlations in Table I indicate that the distribution of asynchronies was not random. Although the reliabilities were not high, they were always positive and nearly all significant. This was true not only overall, but also for each individual voice. Only the subsidiary soprano voice, which included only 12 notes, showed inconsistent results for four pianists, whereas the other six pianists showed their highest

TABLE I. Average between-performance correlations of asynchronies, overall and for each voice separately, in Schumann's "Träumerei." Nonsignificant correlations ($p>0.05$) are indicated.

Pianist	All voices ($n_{max}=223$)	Soprano+ ($n_{max}=12$)	Alto ($n_{max}=55$)	Tenor ($n_{max}=87$)	Bass ($n_{max}=69$)
P1	0.48	0.55	0.37	0.31	0.47
P2	0.56	0.58	0.21 (n.s.)	0.55	0.56
P3	0.69	0.08 (n.s.)	0.61	0.54	0.64
P4	0.53	0.82	0.36	0.46	0.50
P5	0.46	0.17 (n.s.)	0.51	0.41	0.47
P6	0.31	0.03 (n.s.)	0.40	0.31	0.26
P7	0.40	0.78	0.39	0.32	0.37
P8	0.52	0.56	0.53	0.52	0.43
P9	0.50	0.12 (n.s.)	0.55	0.45	0.50
P10	0.66	0.81	0.30	0.62	0.73

reliabilities for this voice. P3 and P10 generally had high reliabilities, suggesting that, far from being careless, they used left-hand leads systematically for expressive purposes. However, pianists who generally led with the right hand and had very tight asynchrony distributions also showed significant reliabilities. Nevertheless, there was evidently a large amount of "motor noise"; the reliabilities usually accounted for less than one third of the variance.

4. Principal components analysis

To reduce the random variability in the data somewhat, the asynchronies were averaged at this point across the three (or two) performances of each pianist. The intercorrelations among the asynchronies of the ten pianists' average performances were then computed. As previously observed for expressive timing in these performances (Repp, 1995b), the intercorrelations were uniformly lower than each pianist's individual reliabilities (Table I), despite the reduction of unsystematic variability in the data; in other words, pianists were more consistent with themselves than with any other pianist. There were a number of nonsignificant and even negative correlations, mainly due to the individual differences in mean asynchronies across voices (Fig. 2).

To determine how many different individual patterns of asynchronies there were, principal components analyses (PCAs) with subsequent Varimax rotation of the significant components were conducted, first on the complete data and then on each voice separately.[14] To be considered significant, a component needed to have an eigenvalue greater than 1 and be associated with the initial steeper-slope section of the eigenvalue plot. For the complete data, two significant components emerged, accounting together for 47% of the variance. The rotated component loadings showed a clear pattern: P3, P2, P10, P4, and P9 had their highest loadings (0.79 to 0.51) on the first component, whereas P5, P8, P1, P7, and P6 had their highest loadings (0.73 to 0.48) on the second component. This result divides the pianists into two groups, those who often led with the left hand and those who did not.[15] They will be referred to as groups I and II in the following.

Similar results were obtained in separate analyses on the tenor and bass voices. These within-voice analyses, unlike the overall analysis, were independent of average tendencies to lead with the left hand (Fig. 2). What they suggest is that the timing of the left hand (relative to the soprano voice in the right hand) across the different positions in the music followed different patterns for groups I and II. The results were different for the alto voice. There was only a single significant component, suggesting that all pianists followed more or less the same pattern of relative onset timing within the right hand.[16]

5. Asynchrony profiles

The component scores from the overall PCA correlated very highly with the average asynchronies of the two groups of pianists (component I versus group I mean: $r=0.989$; component II versus group II mean: $r=0.977$). Therefore, it is appropriate and more straightforward to present the group profiles in terms of average asynchronies. Separate averages for the two groups of pianists were obtained for the tenor and bass voices; for the S+ and alto voices, however, only a single average was calculated across both groups. The data were also averaged over the two renditions of bars 1–8 (a repeat prescribed in the score), which showed very similar patterns of asynchronies. Figure 3 shows the data for groups I and II side by side. Average lag times are plotted as a function of position in the score.[17] The soprano voice reference is represented by the horizontal line at lag zero, the lower right-hand notes by filled symbols, and the left-hand notes by open symbols. A+ and T+ represent subsidiary notes of the alto and tenor voices, respectively. The data for the right hand are identical in the two panels, but the scale is expanded for group II.

The first thing to note is the similarity of the patterns for bars 1–4 and 17–20 in each group; these measures represent identical music. This is another indication of systematicity; the correlations were 0.89 and 0.82 ($p<0.001$) for groups I and II, respectively.

Next, consider the downbeats at phrase beginnings (bars 1-1-1, 5-1-1, 9-1-1, 13-1-1, 17-1-1, and 21-1-1). Here, a low bass note coincides with a soprano note. In group I, the bass led the soprano by some 20 ms in bars 1, 5, 9, and 21, but by about three times as much in bars 13 and 17. These latter positions mark modulations to different keys, which group I pianists gave extra emphasis by anticipating the bass note. Group II pianists, by contrast, did not treat these bars differently. In their playing, the bass always lagged behind the soprano by 20 to 30 ms, as it did in most other positions.

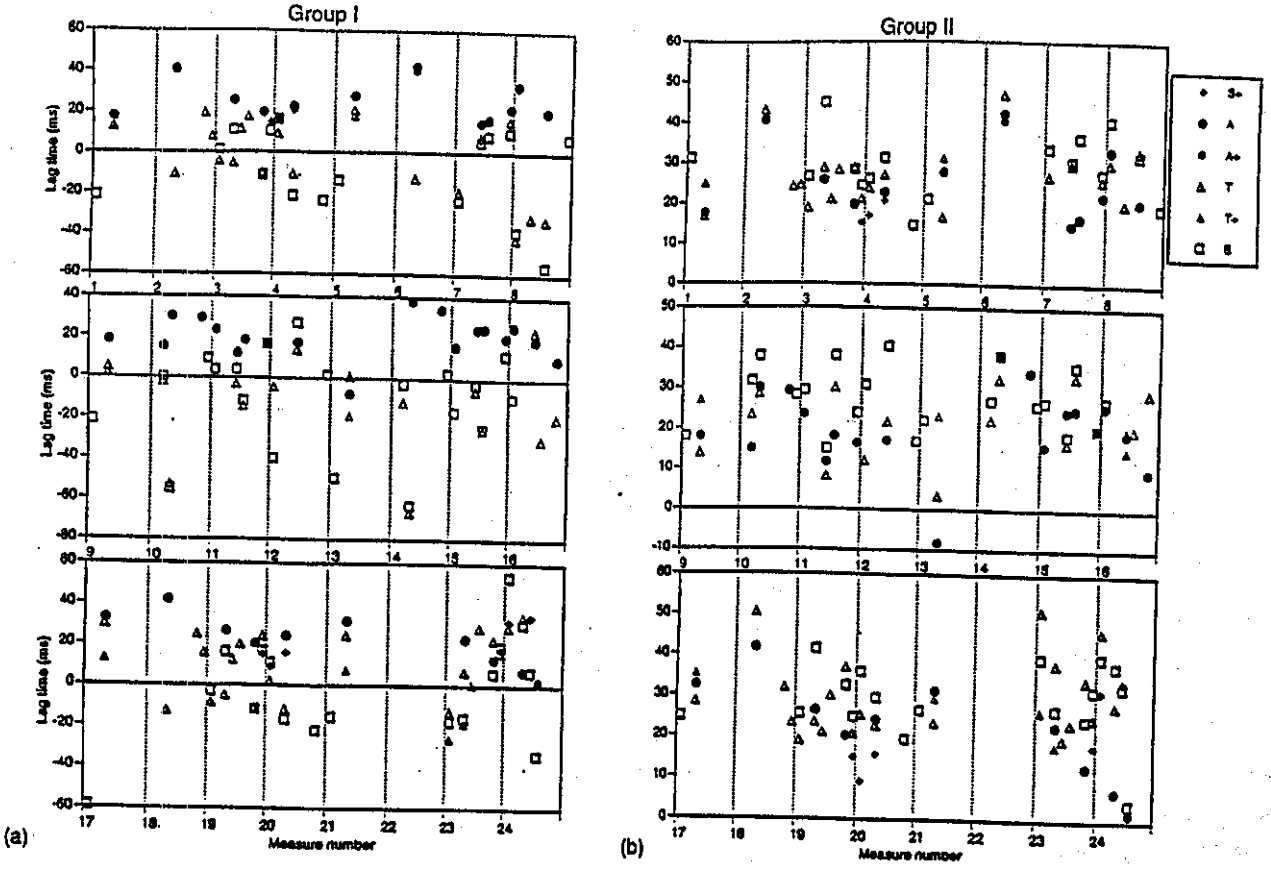

FIG. 3. Average asynchrony profiles of (a) group I pianists (P2, P3, P4, P9, P10) and (b) group II pianists (P1, P5, P6, P7, P8) in Schumann's "Träumerei."

Another striking contrast between the two groups occurs in bars 2-2-1, 6-2-1, and 18-2-1, where three or four notes coincide. In both groups, the alto note(s) in the right hand lagged behind the soprano by some 40 ms, but in group I the left-hand tenor note led slightly whereas it lagged behind even more than the alto in group II.[18] An even larger difference can be seen in the analogous chords at 10-2-1 and 14-2-1, which are preceded by an inner voice entry in the tenor together with the bass (10-1-2, 14-1-2). Group I played the entry almost synchronously with the soprano, but showed a substantial left-hand lead on the following chord. Group II, as usual, lagged all the lower voices.

Additional details may be pursued with the score in hand. However, these examples will suffice to demonstrate that the pianists of group I employed left-hand leads systematically to highlight certain positions in the music, whereas group II showed left-hand lags only. According to psychoacoustic research (e.g., Hirsh, 1959; Pisoni, 1977), asynchronies of up to 20 ms are probably perceived as simultaneities, though Rasch (1978) has demonstrated that even shorter leads can result in perceptual enhancement of the leading tone. However, the purpose of left-hand leads is probably not (or not only) to enhance perception of the lower notes but rather to give emphasis to a melody note by delaying it relative to the left hand.[19] The accent-lending function of a melodic delay may derive from the fact that it is contrary to the velocity artifact: It is the more intense event that is delayed.

6. Asynchronies and dynamics

It is now time to examine to what extent the velocity artifact may account for the pattern of asynchronies, particularly in group II. A detailed analysis of the dynamic microstructure of the "Träumerei" performances has been presented elsewhere (Repp, 1996). The soprano voice melody was more intense than the other voices by 16 MIDI velocity units (about 4 dB), on the average, whereas the other voices did not differ much in their average levels. This in itself is sufficient to account for the average melody leads in group II and in the right hand of group I (Fig. 2). Even stronger evidence for a velocity artifact would be obtained, however, if the dynamic differences between pairs of voices *from position to position* were correlated with the asynchronies between them.

The alto voice asynchronies indeed showed a striking dependence on dynamics: The correlation between the average lag times of the primary alto notes (Fig. 3) and the average velocity differences between alto and soprano was -0.83 ($p<0.001$). The regression line had an intercept close to zero, which indicates that the average lag of the alto voice behind the soprano voice can be attributed entirely to the dynamic difference. The slope of the regression line was -1.67 (i.e., a lag of 1.67 ms per velocity unit), which is consistent with Fig. 1.

To see whether a similar relationship obtained within the left hand, asynchronies between the tenor and bass voices (specially computed for this purpose) were regressed against

their velocity difference, separately for each group of pianists. A smaller but significant correlation was obtained in each case: -0.42 ($p<0.01$) for group I, -0.64 for group II. Again, the intercepts of the regression lines were close to zero, and the respective slopes were -1.55 and -1.49, a little shallower than for the right hand.[20] While the relationship was less tight here, it seems that the temporal relationship of tenor and bass voices was at least partially due to their relative velocities, even in group I.

In contrast to these within-hand relationships, the between-hand asynchronies (tenor and bass relative to soprano) did not show any significant correlations with dynamics in group I. In group II, only the bass voice showed a small trend ($r=-0.37$, $p<0.01$).

B. Debussy's "La fille aux cheveux de lin"

In contrast to Schumann's "Träumerei," this piece is predominantly chordal in nature; there is no polyphonic structure, and the simultaneities are truly vertical sonorities. It was of interest to see whether this would reduce the range of asynchronies and/or the tendency of some pianists to lead with the left hand.

1. Outliers

The number of abnormally large asynchronies excluded from the analyses was larger here than in the Schumann piece. There are four notated *arpeggi* in the score (positions 12-1-1, 36-1-1, 37-1-1, 38-1-1), one notated "split" chord in the left hand (16-1-1), two unnotated left-hand splits (i.e., chords that cannot possibly be spanned and must be divided: 6-3-1, 30-1-1), and one additional left-hand chord that is difficult to span for small hands (32-1-1). These were obligatory outliers, as it were. In addition, full or partial arpeggiation was encountered in other places, where it was not notated (a total of 76 instances in the 29 performances). This was common in positions 6-3-1 and 12-1-1 (left hand), and occurred more idiosyncratically elsewhere, such as in 22-2-3, 23-1-1, 32-1-1 (left hand), and 36-1-1 (right hand). Furthermore, a number of additional splits were observed, usually between the hands (with the left hand leading), sometimes within the left hand (with the bass note leading); some of these occurred in all three of a pianist's performances, others only in one or two (a total of 52 instances). Nearly all of these liberties were due to P2, P3, P4, P6, P9, and P10, who, except for P6, are the group I pianists of the Schumann analysis. Thus the splits may have been just extreme instances of a tendency to lead with the left hand. Nevertheless, the resulting asynchronies were excluded from the following analyses because they were more than four standard deviations from the mean. Finally, there were a number of apparent timing errors (58 instances) that were excluded according to the same criterion; P3 was the only pianist that committed some of those consistently.

2. Asynchrony distributions

When pianists' grand average lag times and standard deviations were computed, high correlations were found with

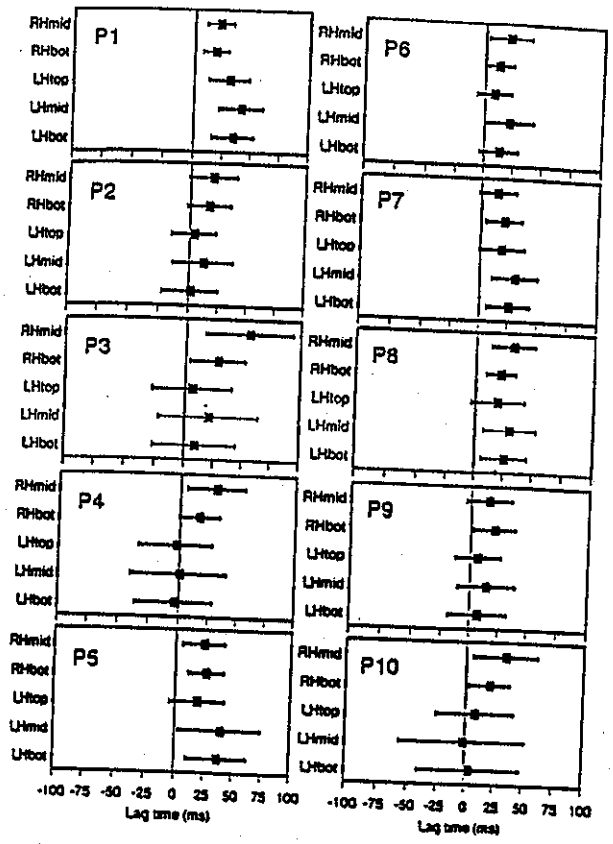

FIG. 4. Average lag times relative to the highest note in each chord plus/minus one standard deviation for the different layers in Debussy's "La fille aux cheveux de lin."

the corresponding statistics in the Schumann piece ($r=0.85$ and 0.93, respectively, $p<0.001$). Thus individual tendencies to lead with the left hand were preserved.

The data were divided into right-hand (within-hand) and left-hand (between-hand) asynchronies. The former were further divided into middle notes and bottom notes (usually played with the thumb), the latter into top notes (usually played with the thumb), middle notes, and bottom notes (usually played with the fifth finger). The division was not based on voice leading but simply on the number of notes in each hand. The right-hand top notes served as the reference. The mean lag times and standard deviations are shown in Fig. 4.

The middle and lower notes in the right hand lagged behind the top notes in all cases. Several pianists (P3, P4, P6, P8, P10) showed longer lag times for the middle notes than for the bottom notes; the others showed little difference. In the left hand, too, there was a tendency for the inner notes to lag a little more than the outer notes. P3, P4, and P10 again showed strong tendencies to lead with the left hand; P2 and P9 showed weaker tendencies; P1 and P5 an opposite tendency.

3. Reliabilities

The reliabilities for all asynchronies, and for the right and left hand separately, are shown in Table II. They are

TABLE II. Average between-performance correlations of asynchronies, overall and for each hand separately, in Debussy's "La fille aux cheveux de lin." All correlations are significant ($p<0.001$).

Pianist	All notes ($n_{max}=321$)	Right hand ($n_{max}=124$)	Left hand ($n_{max}=197$)
P1	0.67	0.38	0.67
P2	0.55	0.46	0.53
P3	0.63	0.53	0.61
P4	0.64	0.61	0.57
P5	0.64	0.53	0.67
P6	0.59	0.52	0.63
P7	0.48	0.51	0.45
P8	0.69	0.64	0.71
P9	0.49	0.47	0.45
P10	0.74	0.57	0.75

somewhat higher than in the Schumann piece. Clearly, there was some consistency in the patterns of asynchronies for both hands, and for all individual pianists.

4. Principal components analysis

As in the Schumann analysis, the intercorrelations among the pianists' average asynchrony profiles were uniformly lower than their individual reliabilities, despite the reduction of noise in the data through averaging. This was also essentially true for each hand separately, though there were a few exceptions.

A PCA on the complete data again yielded two components which together accounted for 53% of the variance. The rotated components divided the pianists into two groups, corresponding to groups I and II of the Schumann analysis. An analysis of the left-hand asynchronies alone yielded a similar result. Again, however, the right-hand asynchronies followed a different pattern. There was evidence for two components, but they divided the ten pianists differently: P8, P6, P10, P3, P1, and P4 versus P5, P9, P7, and P2. The pianists in the first group tended to lag middle notes more than bottom notes, whereas the pianists in the second group tended toward the opposite (see Fig. 4). This difference will not be considered further here as it is of marginal interest.

5. Asynchrony profiles

The data for groups I and II are shown in Fig. 5. The right-hand averages were computed for each group separately in this instance. The structure of the Debussy prelude is more irregular than that of Schumann's "Träumerei," and there are few passages that are repeated literally. Different sections of the piece are characterized by different types of collaboration between the hands.

The first ten bars have a melody in the soprano voice, harmonically supported by chords that are distributed between the two hands. In both groups of pianists, right-hand lags hovered between 10 and 40 ms, except for two rather delayed notes (F_4) in bar 5 in group I. The left hand gener-

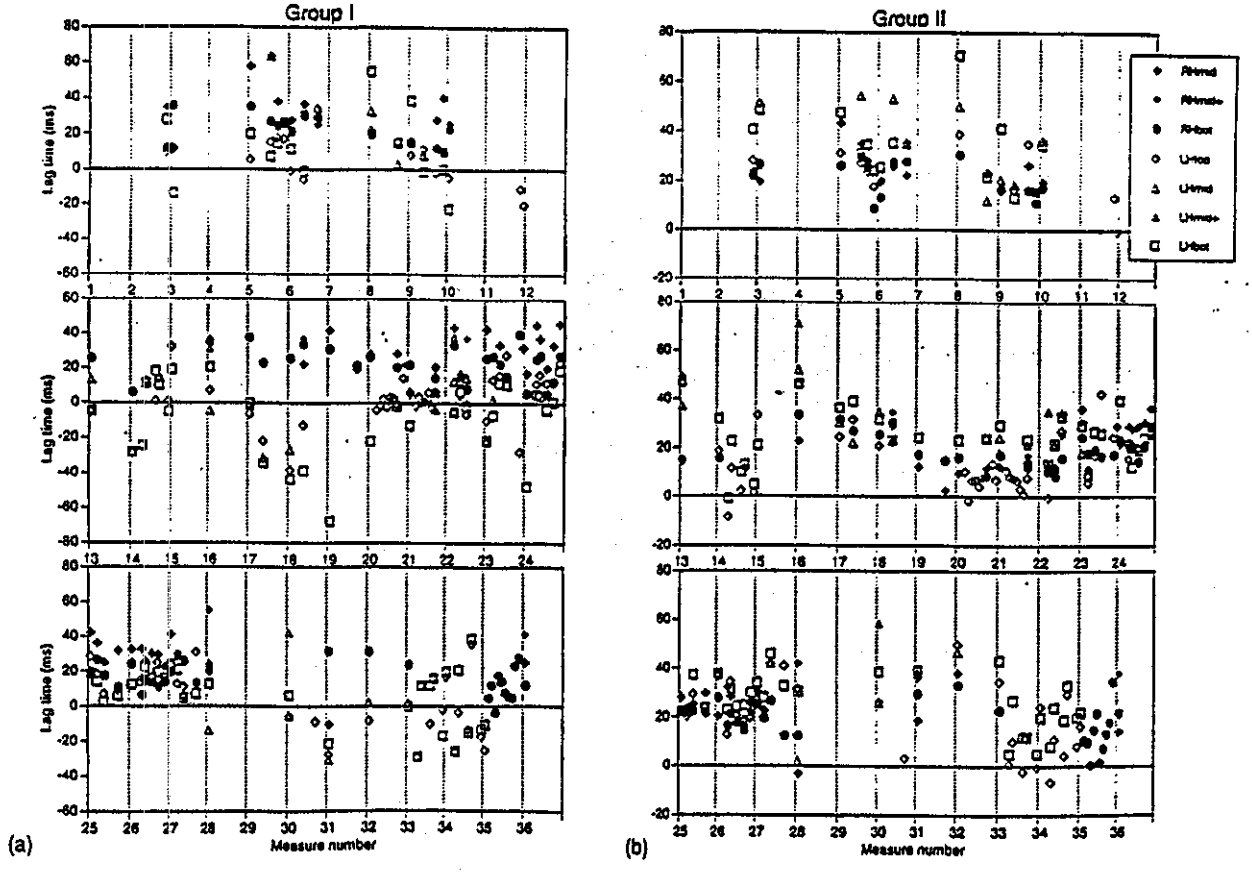

FIG. 5. Average asynchrony profiles of (a) group I pianists (P2, P3, P4, P9, P10) and (b) group II pianists (P1, P5, P6, P7, P8) in Debussy's "La fille aux cheveux de lin." The "+" entries in the legend indicate additional notes in chords having more than three notes in one hand.

ally lagged behind even further in group II, whereas in group I it tended to lag less and even lead on occasion. Slight left-hand leads were observed in positions 3-1-1 and 10-1-1, where the left hand plays an open fifth. (However, only a single "split"—excluded as an outlier—occurred in these two positions.)

A different texture occurs in bar 14, where the soprano voice alternates rapidly with chords moving in parallel; this passage recurs in similar form in bars 33 and 34. In group II, the left hand sometimes coincided with the right hand here or even led very slightly, though most of the time it lagged behind. In group I, stronger left-hand leads can again be observed. What both groups have in common here, though this is difficult to see in the graphs, is a pronounced tendency to play the left-hand notes earlier in the anacrusic positions (14-1-4, 14-2-4, 14-3-4, etc.) than when they occur on the beat (14-2-1, 14-3-1, 15-1-1, etc.).

Bars 16 through 19 have again a soprano melody with chordal accompaniment. Here the differences between the two groups are most striking. In position 16-1-1, the left hand tended to be synchronized with the right hand in group I, but it lagged strongly in group II. In the following positions, left- and right-hand notes lagged equally behind the soprano voice in group II, but in group I some of the largest left-hand leads occurred; in fact, there was a progressive increase in lead time. The bass note in position 19-1-1 showed an average lead of about 70 ms in group I, compared to an average lag of more than 20 ms in group II. (A number of large splits and *arpeggi* occurred in these bars as well, typically in group I pianists.)

In bars 20 and 21, there are parallel octave runs ending in chords. Even in these scalelike bimanual passages, group II pianists had a slight but consistent tendency to lag with the left hand, whereas in group I the two hands were generally synchronous. In the chords, as in the following bars 22 and 23 (which are a variation of bars 17 and 18) and 30 to 32, the tendency of group I to occasionally lead with the left hand is again exhibited. Bars 24 through 28 contain parallel chords in both hands, and here both groups played similarly, without left-hand leads, though relatively speaking the left hand still came in earlier in group I than in group II. Finally, there is a brief passage of right-hand dyads in bar 35; these were played by both groups with the lower note progressively lagging.

In summary, this comparison shows that, while group I generally tended to advance the left hand more than did group II, this difference was more pronounced in passages characterized by a functional differentiation of the two hands, viz., melody versus harmonic support. Where the two hands have more similar roles, as in parallel scales and distributed chords, the differences between the groups were smaller.

6. Asynchronies and dynamics

The right-hand asynchronies were averaged across all pianists and regressed against the average velocity differences between the corresponding notes. There was a correlation of -0.60 ($p<0.001$), and the regression line had a slope of -1.11 and a small intercept (7 ms). The correlation was lower than in the Schumann piece and the slope was correspondingly shallower, but clearly there was again a relation to relative velocity. Within the left hand (with the top notes serving as the reference), the analogous correlations were -0.65 for group I and -0.76 for group II. The regression lines had slopes of -2.22 and -1.91, respectively, almost twice as steep as for the right hand, and the respective intercepts were -6 and -1 ms. Since the left hand played softer than the right hand, the steeper slopes are consistent with the velocity artifact (Fig. 1). Finally, the correlation between the between-hand asynchronies and velocity differences was assessed. It was weak for group I ($r=-0.31$, $p<0.001$) but substantial for group II ($r=-0.61$). The slopes were -0.74 and -1.37, respectively, and the intercepts were -8 and 2 ms. The small intercepts and moderately high correlations suggest that asynchronies were in part a consequence of velocity differences, especially in group II.

C. Chopin's Prelude in D-flat major

This piece is longer than the preceding two, comprising 89 bars. It has a tripartite structure, and the sections have very different textures. The initial section (bars 1–27) and its abbreviated recapitulation (bars 76–89) feature a soprano melody with a left-hand accompaniment consisting of sparse chords alternating with pulsating bass notes. The right hand is purely monophonic here, except in the final bars (84–89). In the middle section, a two-voiced melody in the left hand is accompanied by pulsating notes in the right hand which grow into octaves and then into chords with a prominent inner voice. This passage, which is repeated once (bars 28–44, 45–59), provides an opportunity to study the effects on asynchronies of a shift of the melodic lead to the left hand and of prominence given to inner notes of chords in the right hand (cf. Palmer, in press). The transitional section following the climax (bars 60–75) returns melodic dominance to the right hand, which now has full chords in which the melody shifts back and forth between the top notes and inner notes, while pulsating eighth notes continue below the melody, played by the same hand. These shifting emphases make this piece the most interesting of the three from the perspective of asynchronies.

1. Outliers

In contrast to the Debussy Prelude, this music did not invite arpeggiation of chords; there were only ten instances overall. Split chords, on the other hand, were very frequent; 159 instances were excluded as outliers. They were clearly used for expressive purposes in certain positions in the music, and the left hand always led the right. While splits between soprano and bass notes were rare on the first downbeat of the first statement of the theme (positions 1-1-1, 20-1-1, 76-1-1; $n=4$), they were common on the downbeat of the repeated statement which is preceded by an embellishment of the soprano melody (positions 5-1-1, 24-1-1, 80-1-1; $n=33$). Splits were especially frequent at the beginning of the embellishment (positions 4-4-1, 23-4-1, 79-4-1; $n=41$). P3, P9, and P10 were particularly prone to splits, though all pianists contributed some. The remaining outliers were mostly late notes ($n=45$) and a few early notes ($n=6$), some

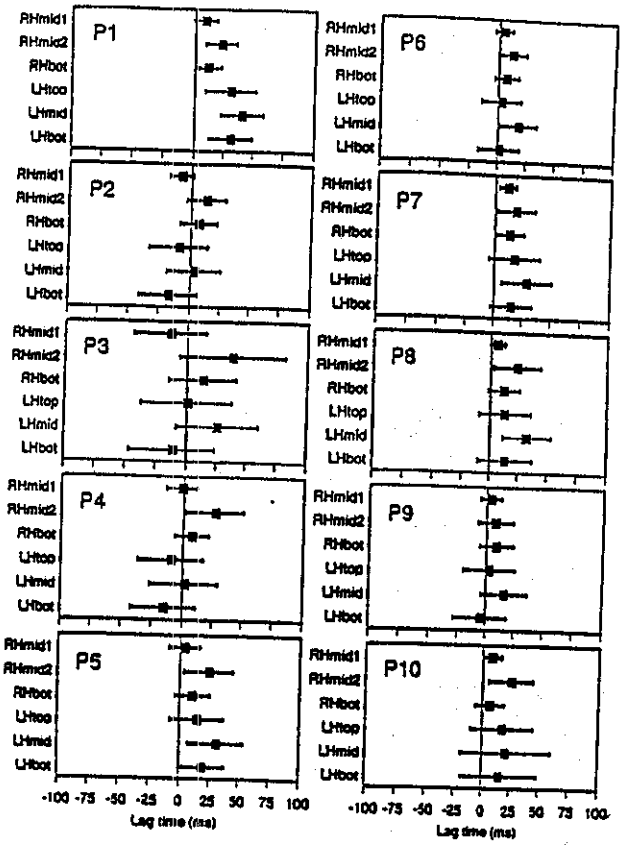

FIG. 6. Average lag times relative to the highest note in each chord plus/minus one standard deviation for the different layers in Chopin's Prelude in D-flat major.

of which represented rhythmic errors: for example, two pianists played the eighth-note octaves in positions 41–42 and 57–62 consistently as sixteenth notes.

2. Asynchrony distributions

The pianists' grand average lag times correlated strongly with those in the Schumann piece ($r=0.78$, $p<0.01$) and in the Debussy Prelude ($r=0.85$), as did the standard deviations ($r=0.95$ and 0.88, respectively). Again, individual differences seemed to be preserved.

As in the Debussy Prelude, the data were divided into right-hand (within-hand) and left-hand (between-hand) asynchronies. The former were further divided into middle notes and bottom notes (usually played with the thumb), the latter into top notes (usually played with the thumb), middle notes, and bottom notes (usually played with the fifth finger). The lower notes of the left-hand dyads in bars 1–27 and 76–89 were classified as middle notes. The prominent right-hand middle notes in bars 36–42 and 52–58 (Type 1) were further distinguished from the less prominent middle notes in bars 60–75 (Type 2). The individual mean lags and standard deviations for these six categories are shown in Fig. 6.

The by now familiar individual differences between group I and group II pianists can again be seen, with only P10 showing no average tendency to lead with the left hand here, but large standard deviations instead. Even more clearly than in the Debussy piece, there is a tendency for inner notes of chords to lag behind outer notes, in both hands. The exception to this rule are the type 1 inner notes in the right hand, which tend to lead the bottom notes and, in some pianists (P2, P3), even the top notes. They also generally have the smallest standard deviations. This provides clear evidence of an effect of relative prominence on asynchronies, a likely consequence of an increase in relative intensity. At the individual level, the parallels between the Debussy and Chopin results (disregarding the RHmid1 asynchronies) are striking, despite the often different functional roles of the "voices"; only P10 shows a change in the pattern of between-hand coordination.

TABLE III. Average between-performance correlations of asynchronies, overall and for each hand separately, in Chopin's Prelude in D-flat major. All correlations are significant ($p<0.001$).

Pianist	All notes ($n_{max}=774$)	Right hand ($n_{max}=304$)	Left hand ($n_{max}=470$)
P1	0.76	0.63	0.70
P2	0.64	0.60	0.59
P3	0.61	0.60	0.60
P4	0.60	0.56	0.54
P5	0.64	0.65	0.61
P6	0.58	0.51	0.59
P7	0.59	0.54	0.59
P8	0.76	0.77	0.75
P9	0.59	0.54	0.59
P10	0.53	0.49	0.53

3. Reliabilities

The reliabilities are shown in Table III. They are similar in magnitude to those in the Debussy Prelude. The patterns of both within-hand (right-hand) and between-hand (left-hand) asynchronies were replicable to some extent from one performance to the next.

4. Principal components analysis

Once again, the intercorrelations among the pianists' average asynchrony profiles were uniformly lower than their individual reliabilities, despite the reduction of noise in the data through averaging. This was also essentially true for each hand separately, though there were a few exceptions. The PCA, too, brought few surprises. In the overall analysis, two components accounted for 57% of the variance. The loadings on the rotated components defined group I and II, as previously. P6 loaded almost equally highly on the two components, and P10 had a rather low loading on the group I component, but an even lower one on the group II component. A separate analysis on the left-hand (between-hand) asynchronies yielded a similar result, except that now P2 and P9 loaded almost equally highly on the two components. The PCA on the right-hand asynchronies yielded a different result: The first component was defined by P5, P4, P2, P3, P1, and P9, whereas the second component represented P6, P10, P7, and P8. This grouping is quite different from that obtained in the Debussy analysis. However, before Varimax rotation, the first component accounted for 50% of the variance but the second for only 12%, so that the pattern of right-hand asynchronies may be considered fairly homogeneous.

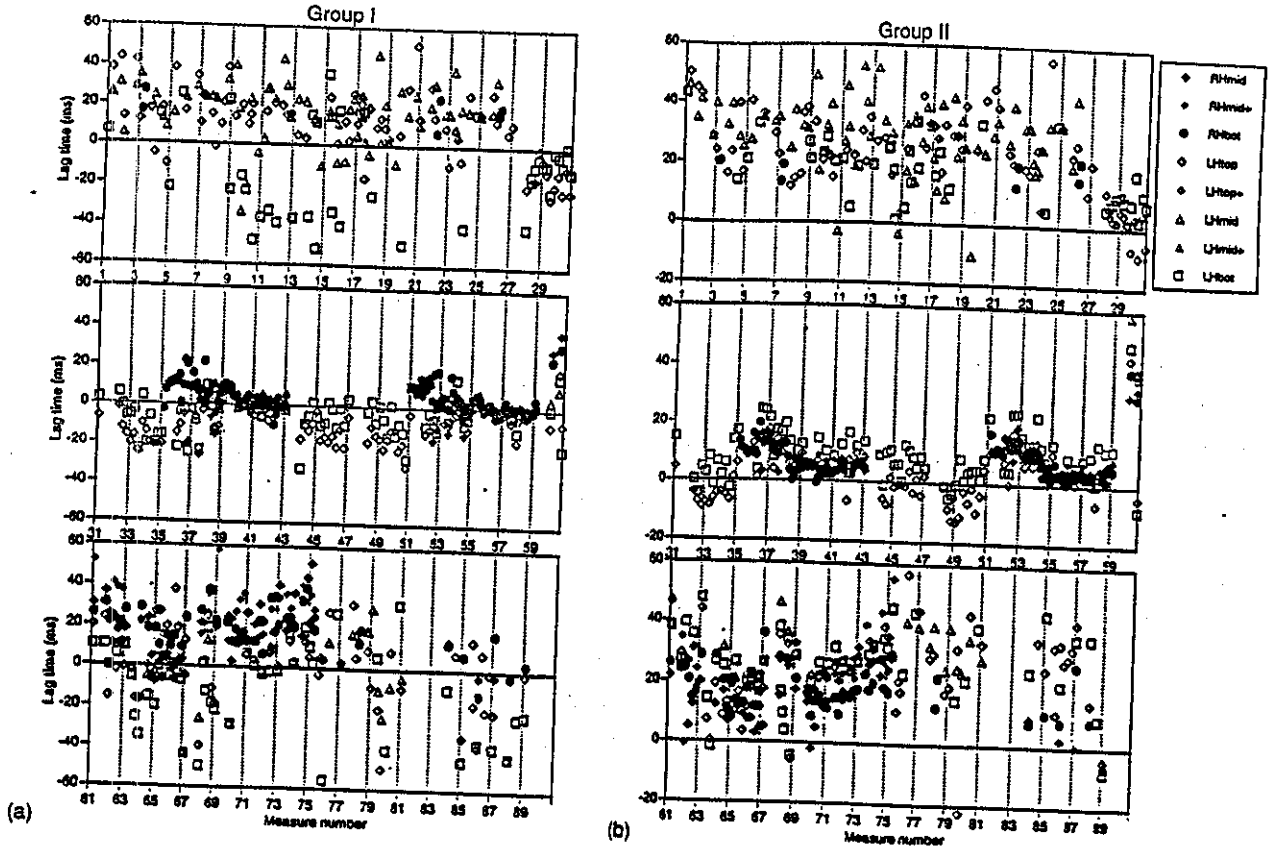

FIG. 7. Average asynchrony profiles of (a) group I pianists (P2, P3, P4, P9, P10) and (b) group II pianists (P1, P5, P6, P7, P8) in Chopin's Prelude in D-flat major. The "+" entries in the legend indicate additional notes in chords having more than three notes in one hand.

5. Asynchrony profiles

The asynchrony profiles of groups I and II are shown in Fig. 7. As in Fig. 5, average right-hand asynchronies were computed separately for each group. The top panels (up to bar 27) and the right-hand portions of the bottom panels (from bar 76 to the end) show sections of the music where the left hand accompanies a right-hand melody. Once again, the most striking difference between the two groups is in the timing of the left-hand bottom notes, which typically lead by 20–50 ms in group I, but lag by up to 40 ms in group II. There are some instances of lagging bottom notes in group I; closer inspection reveals that they all occur between beats (positions 4-2-2, 8-4-2, 14-1-2, 14-2-2, 15-1-2, 15-2-2, 15-4-2, 17-1-2, 17-2-2, 79-2-2) or on the fourth beat (positions 5-4-1, 24-4-1, 76-4-1, 80-4-1), whereas the leading bottom notes occur on strong beats. The middle and top notes of the left hand, which nearly always occur as dyads, usually lag behind the right hand in both groups, with the middle notes lagging more than the top notes. In some instances the left-hand dyad occurs without a right-hand melody note, so that the asynchrony of the middle note was computed relative to the top note in the left hand; in some of those instances, the middle note tended to lead (positions 10-4-1, 14-4-1, 19-3-1). In the final bars, where the pulsating eighth notes are top notes in the left hand, they tended to lead the right hand in group I.

In the middle section of the piece, three types of passage can be distinguished. In the first type (bars 28–34, repeated in bars 44–50), left-hand melodic dyads occur below pulsating eighth notes in the right hand. In group I, the left hand tended to lead by up to 20 ms, with the melodically more important top notes leading more than the bottom notes. In group II a similar differentiation can be seen, but the asynchronies hovered around the point of synchrony. Compared to the strong left-hand lags of group II elsewhere, however, there is clear evidence for a temporal advancement of the left-hand melody notes.

The passage of the second type (bars 35–43, repeated in bars 51–60) is divided into two halves of 4 bars each. In the first half, the dyadic left-hand melody is accompanied by pulsating octaves in the right hand that bracket melodic middle notes an octave above the upper voice of the left hand, and there is a strong *crescendo* during these bars. In group I the left-hand leads decreased as the dynamics increased; in group II, on the other hand, the left hand started to lag as soon as the right-hand octaves started, and these lags decreased somewhat with increasing dynamics. Both groups showed a clear tendency for the bottom notes of the right-hand octaves to lag by up to 20 ms behind the top notes; this tendency again decreased during the *crescendo*. Some of the right-hand middle notes tended to lead in group I, but not in group II. During the climactic second half, the left hand has *fortissimo* octaves and the right-hand middle notes become dyads, while the pulsating eighth-note octaves continue. Here group I showed virtual synchrony of all notes, but group II still showed a very slight lag of the right-hand

middle and bottom notes and a somewhat greater lag (about 10 ms) of the left-hand bottom notes.

The passage of the third type (bars 60–75) is the technically most difficult one and gave rise to many inaccuracies which are documented elsewhere (Repp, in press). The asynchronies were correspondingly variable. Both groups showed right-hand lags of up to 40 ms, with the middle notes typically lagging more than the bottom notes, regardless of whether the pulsating eighth notes are in the middle (bars 60–63 and 68–70) or at the bottom (bars 64–67 and 71–75). The left hand was particularly variable here in both groups, but there was the familiar group difference in bottom notes and occasionally top notes, which tended to lead in group I but to lag in group II. A more orderly pattern can be observed in bars 71–75, where there were no left-hand leads in group I (though the left hand was still in advance of right-hand middle and bottom notes) and left-hand lags in group II were between 20 and 40 ms, similar to right-hand middle notes but later than right-hand bottom notes.

This descriptive analysis shows that asynchronies depend very much on the function the notes subserve, and indeed the graphic patterns in Fig. 7 nicely delineate the structural sections of the music. The question remains to what extent these changing patterns were mediated by changing dynamic relationships.

6. Asynchronies and dynamics

A strong relationship between asynchronies and dynamics was indeed found once again. Within the right hand, averaged across all ten pianists, the correlation was −0.92, the highest obtained yet; the slope of the regression line was −1.3, and the intercept was 3 ms. Within the left hand, the correlation was −0.82 for group I and −0.76 for group II; the respective slopes were −2.21 and −1.39—again much steeper than for the right hand—and the intercepts were −5 and −1 ms. Finally, the between-hand asynchronies and velocities showed correlations of −0.55 ($p<0.001$) and −0.82 for the two groups; the slopes were −0.76 and −0.99, and the intercepts were −7 and 9 ms, respectively. The lower correlation for group I was due to a distinct swarm of data points that deviated from the general trend, having negative lag times where positive lag times were predicted by the regression equation. Of course, these were exactly the notes that tended to be anticipated by the left hand; the analysis merely confirmed that this anticipation was an expressive strategy and not a consequence of the relative intensity of these notes. Elsewhere, however, the asynchronies were a likely consequence of the velocity artifact.

III. DISCUSSION

The present study complements and extends previous studies of onset asynchronies in keyboard performance, most of which employed smaller samples of music or musicians, or were representative of earlier performance styles. The 10 (pianists)×3 (pieces)×3 (renditions) design made possible a systematic exploration of individual differences, of their consistency across different pieces, and of the reliability of asynchrony patterns across repetitions of the same music. The pianists' technical skill is representative of that of professional musicians at the beginning of their career. The main limitation of this study is that the performances were recorded after only minimal rehearsal and hence were not "polished." This may have increased uncontrolled variability and may also have encouraged systematic between-hand asynchronies such as observed in the group I pianists. Nevertheless, to emerge under these conditions, such tendencies must have been latently present, and it seems unlikely that they would disappear entirely with practice. On the contrary, the temporal coordination of fingers and hands in pianists presumably depends on highly overlearned skills and strategies that are applied automatically in any performance situation.

The present analyses suggest that systematic variation in asynchronies is to a large extent a consequence of expressive dynamic differentiation, especially within each hand—the velocity artifact. Although the correlation between asynchrony and relative intensity does not prove a causal connection between these two variables, it seems plausible that pianists aim for synchrony of finger-key contacts. This is suggested by the very small intercepts of the regression lines: When there is no difference in hammer velocity, there is no asynchrony either. The general magnitudes of the regression slopes (1–2 ms per velocity unit) and the larger slopes for the left hand than the right are also consistent with the velocity artifact (Fig. 1), taking into account that random variability in the data reduces the slope of a regression line.

There is an apparent discrepancy with the findings of Palmer (1989, in press), who found no consistent correlation between lag time and velocity difference, even in the same Chopin Prelude (Palmer, in press).[21] The reasons for this may lie in the way the correlations were computed: Palmer averaged across several nonmelodic voices and considered each pianist separately, whereas here pairs of individual voices were compared after averaging across pianists. The present method reduced random variability more effectively, and there was also a larger number of data points. It is possible, however, that some of Palmer's more experienced pianists had learned to compensate for the velocity artifact by striking keys asynchronously. The fact that Palmer measured key-bed contact rather than hammer impact asynchronies cannot account for the different findings, as the velocity artifact should be even more pronounced in the former than in the latter (Askenfelt and Jansson, 1990).

Clearly, the temporal relationship between the two hands is more flexible than that among fingers of the same hand. There was only weak evidence for a between-hand velocity artifact in the present data, though this could also have been due to larger random variability in between-hand than in within-hand asynchronies. The average left-hand lags of the group II pianists in the present study are consistent with the velocity artifact. The left-hand leads of group I pianists, however, obviously constitute an expressive strategy, whether or not the pianists were conscious of it. One main finding of the present study is that there are individual differences among pianists in their tendency to lead with the left hand, and that these differences are consistent across rather different pieces of music. Although the extreme left-

hand leads heard on some historic recordings seem to be a thing of the past, a smaller tendency in the same direction seems to be alive and well among today's young pianists.

The question of handedness is likely to come to mind here. Stucchi and Viviani (1993) have reported that, in simultaneous drawing movements with both hands, the dominant hand tends to lead the nondominant hand by about 25 ms. Could the difference between groups I and II then have been due to handedness? This question can be answered confidently in the negative: All group I pianists considered themselves right handed. Among group II pianists, however, there were two left handers (P5 and P7). Thus there seems to be no relation between hand dominance and a tendency to lead with that hand. That tendency must reflect either an unconscious habit or a deliberate strategy (perhaps both) acquired during training. Conversations with several of the group I pianists suggested that they were aware of their left-hand leads but seemed to regard them more as a habit than as a deliberate strategy (cf. footnote 3). How this habit is acquired is presently unknown. The pianists came from different conservatories and diverse backgrounds, and six of them had barely begun their graduate studies, so that a common teacher can be ruled out as a factor.[22]

The perceptual and aesthetic effect of left-hand leads seems to be an accentuation of the delayed melody note, similar to that conveyed by a grace note or *arpeggio*. At the same time, the lower note stands out more clearly by virtue of its lead time, and this may reinforce the bass line or harmony. The expressive effect of left-hand leads derives largely from the fact that it runs counter to the velocity artifact (if the right-hand melody is the strongest voice). Although small right-hand leads, such as may result from the velocity artifact, may help to enhance the melody (Rasch, 1978), large right-hand leads (>100 ms) are hardly ever observed. The fact that left-hand leads lend themselves to exaggeration whereas right-hand leads do not suggests that only the former represent an expressive strategy. This strategy comes with a certain risk, for while it may often be effective locally, it can easily sound mannered or sloppy if applied indiscriminately or too frequently.

Palmer (1989, in press) found that melody leads were more pronounced in metrically strong than in metrically weak positions. The present data were not analyzed systematically with regard to metrical effects, in part because of the heterogeneity of musical events occurring in different metrical positions, which makes it difficult to attribute any effects to metrical strength alone. In Schumann's "Träumerei," the analysis is further complicated by a structural de-emphasis of downbeats. In that music, there are a number of metrically weak–strong, multivoiced harmonic progressions (7-2-2 to 7-3-1, 7-4-2 to 8-1-1, 10-1-2 to 10-2-1, 11-2-2 to 11-3-1, 11-4-2 to 12-1-1, 14-1-2 to 14-2-1, 15-2-2 to 15-3-1, and 15-4-2 to 16-1-1) in each of which group I showed an increase in left-hand lead from the first to the second chord, whereas group II showed an increase in left-hand lag (see Fig. 3). These effects may well reflect metrical strength, but they may also be due to the resolution of a dissonant chord into a more consonant one. In any event, the two groups of pianists reacted with opposite strategies. Group I also marked the beginnings of new phrases with left-hand leads, whereas group II showed merely their typical left-hand lags. In the Debussy Prelude, however, a passage was found in which group I pianists showed greater left-hand leads in a metrically weak (anacrusic) than in a metrically strong position.

Metrical effects (i.e., effects due to metrical structure alone) should emerge most clearly in sections of relatively homogeneous texture. In the Debussy Prelude, one such section occurs in bars 24–27, but neither group of pianists showed a systematic pattern of asynchronies as a function of metrical position. In the Chopin Prelude, Palmer (in press) found for the initial section (bars 1–27) that melody leads were more pronounced in on-beat than in off-beat positions. Inspection of the music reveals, however, that opportunities to observe off-beat asynchronies are less frequent than opportunities to observe on-beat asynchronies, especially in the second halves of measures, and that there is a systematic difference in the left-hand notes between these positions. This confounds the comparison. In bars 10, 11, 14, 15, and 17, where several consecutive eighth notes occur in the melody, the present group I showed left-hand leads on beats 1 and 3, but left-hand lags in between; this difference may or may not be metric in origin. Group II showed no clear pattern. A better opportunity to observe metrical effects is offered by the middle section, where a left-hand melody in quarter-note dyads is pitted against repeated eighth notes in the right hand (bars 28–39 and 44–55). However, there was no trace of a metrical pattern in these sections for either group of pianists. Thus the present data offer no direct support for Palmer's contention that asynchronies vary with metrical strength: some of the apparently metrical variation may be due to other factors, such as different dynamic strengths of the notes involved (i.e., the velocity artifact).

In conclusion, the results of the present analyses confirm that note onset asynchrony is a parameter that can serve structural and expressive functions. To a considerable extent, however, its systematic variation seems to be a consequence of variation in dynamics—the velocity artifact. Only those asynchronies that run counter to the velocity artifact may represent a deliberate expressive strategy. Such a strategy was seen in some young pianists' tendency to lead with the left hand, which seems to be modeled on the style of an earlier generation of pianists.

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[1]Strictly speaking, there is no such thing as an asynchrony among notes because—contrary to popular usage of the term—notes are just symbols of musical notation (analogous to letters in writing), not sounds. They are simultaneous when they are in the same metrical position (usually aligned vertically) in the printed score, and successive otherwise.

[2]Hartmann gives measurements in fractions of centimeters but does not mention the playback speed of the piano roll.

[3]Interestingly, this pianist "reported that this was a habit acquired quite early in life, and one which, in recent years, he has been trying to modify" (Henderson, 1936, p. 299).

[4]Vernon (1936) also raised the question of the perceptibility of asynchronies. On the basis of a small experiment with isolated two-tone chords he concluded that trained musicians can detect asynchronies smaller than 20 ms, in some cases as small as 8 ms. These observations were supported by a more detailed study carried out later by Rasch (1978). Rasch measured the detection threshold for a complex tone in quiet, when it was accompanied by a lower-frequency complex tone, and when the onset of that lower tone was delayed by small amounts. He found that the threshold for the higher tone decreased by about 10 dB for every 10 ms of lower-tone delay and reached the quiet threshold at a 30-ms delay. This suggests that even very brief asynchronies can enhance the perception of the leading tone substantially. At the same time, a brief asynchrony may be difficult to perceive *as such*. Rasch comments that "the two notes are perceived as two separate but simultaneously occurring sounds" (p. 29). Asynchronies have been employed as a means of enhancing and segregating individual components of complex sounds in many psychoacoustic studies (e.g., Bregman and Pinker, 1978; Darwin and Ciocca, 1992).

[5]By coincidence, the same composition was included in the present study.

[6]A fourth piece, "Erotik" (No. 5 of the Lyric Pieces, op. 43) by Edvard Grieg, was recorded but not analyzed for asynchronies because it contains a large number of arpeggiated chords that are the subject of a separate study (Repp, submitted).

[7]The score of "Träumerei" may be found in Repp (1992, 1994, 1996), that of the Chopin Prelude in Repp (in press).

[8]This appears to have been a limitation of the scanning mechanisms in the upright Disklavier: it was discovered only when the asynchronies were tabulated and found to be quantized (rounded to the nearest millisecond). More recent recordings from Disklavier grand pianos have a resolution of 1 ms or less.

[9]Of course, no asynchrony was obtained for omitted notes. However, when the highest note in a chord had been omitted (which happened only rarely), it was assigned the onset time of the next-lower note, so that the asynchrony of the latter was zero.

[10]It should be remembered that the "note onsets" in a MIDI file represent hammer impact times, not key surface contact times. The solenoids, although they operate on the distal parts of the key levers, substitute for the pianist's fingers and thus need to be timed so as to achieve the hammer impact times specified in the MIDI instructions. A similar "transport delay correction procedure" (Moog and Rhea, 1990) is in effect on the Bösendorfer 290 SE piano used by Palmer (in press), although MIDI note onsets are recorded at the key bed.

[11]Although the MIDI velocity scale ranges from 0 to 127, the range from 30 to 100 almost spans the full dynamic range of the instrument. The precise relationship between MIDI velocity and (final) hammer or key velocity was not determined.

[12]An external "prelay" function based on Fig. 1 and written in MAX (a graphic programming language for MIDI applications) resulted in undistorted MIDI playback on this instrument.

[13]For the sake of consistency in the assignment of voices to hands, both notes played by the right hand in this chord were assigned to the alto, whereas the two left-hand notes were assigned to the tenor, even though the lower alto note is below the higher tenor note.

[14]The S+ data were not subjected to a PCA because of the small number of data points.

[15]P9 occupied a borderline position, having a moderate loading on the second component as well.

[16]No PCA was conducted on asynchronies within the left hand (i.e., between the tenor and bass voices), but the results would probably have differentiated groups I and II once again.

[17]The figure may be rotated clockwise by 90 deg and read vertically, with real time along the abscissa and score position along the ordinate.

[18]As mentioned above under "Outliers," P9 (group I) always showed a very substantial lead of the tenor note here, which was not included in the averages.

[19]Given the short time intervals involved and the large variation in expressive timing (see Repp, 1995b), it is hard to tell which note in an asynchronous chord is "on the beat" and which is anticipated or delayed.

[20]It should be kept in mind that the slope of the regression line decreases with the correlation between two variables.

[21]Palmer employed only the first section of the Prelude where the asynchronies are mainly between hands; this may account for the low correlations.

[22]The only exception are P1 and P5 (both group II pianists) who had the same teacher as undergraduates.

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