Melody lead in piano performance: Expressive device or artifact?

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As reported in the recent literature on piano performance, an emphasized voice (the melody) tends to be played not only louder than the other voices, but also about 30 ms earlier (*melody lead*). It remains unclear whether pianists deliberately apply melody lead to separate different voices, or whether it occurs because the melody is played louder (*velocity artifact*). The velocity artifact explanation implies that pianists initially strike the keys simultaneously; it is only different velocities that make the hammers arrive at different points in time. The measured note onsets in these studies, mostly derived from computer-monitored pianos, represent the hammer-string impact times. In the present study, the finger-key contact times are calculated and analyzed as well. If the velocity artifact hypothesis is correct, the melody lead phenomenon should disappear at the finger-key level. Chopin's Ballade op. 38 (45 measures) and Etude op. 10/3 (21 measures) were performed on a Bösendorfer computer-monitored grand piano by 22 skilled pianists. The hammer-string asynchronies among voices closely resemble the results reported in the literature. However, the melody lead decreases almost to zero at the finger-key level, which supports the velocity artifact hypothesis. In addition to this, expected onset asynchronies are predicted from differences in hammer velocity, if finger-key asynchronies are assumed to be zero. They correlate highly with the observed melody lead.
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I. INTRODUCTION

Simultaneous noted in the printed score (chords) are not played strictly simultaneously by pianists. An emphasized voice is not only played louder, but additionally precedes the other voices typically by around 30 ms; this phenomenon is referred to as *melody lead* (Hartmann, 1932; Vernon, 1937; Palmer, 1989, 1996; Repp, 1996b). It is still unclear whether this phenomenon is part of the pianists' deliberate expressive strategies and used independently from other expressive parameters (Palmer, 1996), or whether it is mostly due to the timing characteristics of the piano action (*velocity artifact*, Repp, 1996b), a result of the dynamic differentiation of different voices. Especially in chords played by the right hand, high correlations between hammer velocity differences and melody lead times (between melody notes and accompaniment) seem to confirm this velocity artifact explanation (Repp, 1996b).

The data used in previous studies, derived mostly from computer-monitored pianos, represent asynchronies at the hammer-string contact points. The present study examined asynchrony patterns at the finger-key contact points as well. Finger-key asynchronies represent what pianists initially do when striking chords. If the velocity artifact explanation is correct, the melody lead phenomenon should disappear at the finger-key level. This means that pianists tend to strike the keys almost simultaneously, and it is only the different dynamics (velocities) that result in the typical hammer-string asynchronies (*melody lead*).

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A. Background

In considering note onset asynchronies, one has to differentiate between asynchronies that are indicated in the score (arpeggios, apoggiaturas) and asynchronies that are performed but not especially marked in the score. The latter come in two kinds: (1) The melody precedes other voices by about 30 ms on average (*melody lead*), or (2) the melody lags behind the other voices. Asynchronies of the second type occur mainly between the two hands and usually show much larger timing differences (over 50 ms). A typical example would be when a bass note is played clearly before the melody (*melody lag* or *bass lead*), which is well known from old recordings of piano performances, but has been observed in contemporary performances too (Palmer, 1989; Repp, 1996b). Asynchronies of the first type are common within one hand (especially within the right hand, as the melody often is the highest voice), but may also occur between the hands.

Note asynchronies have been studied since the 1930s, when Hartmann (1932) and the Seashore group (Vernon, 1937) conducted the first objective investigations of piano performances. Hartmann used piano rolls as a data source and found mostly asynchronies of the second type. Vernon (1937) differentiated between asynchronies *within* one hand and asynchronies *between* different hands. For the former he observed melody lead (type 1), whereas the latter mostly showed bass note anticipation (type 2).

In the recent literature, Palmer (1989, 1996) and Repp (1996b) have studied the melody lead phenomenon. Palmer (1989) used electronic keyboard recordings to analyze chord asynchronies, among other issues. Six pianists played the beginning of the Mozart Sonata K. 331 and of Brahms' Intermezzo op. 117/1 (''Schlaf sanft, mein Kind...''). The melody led by about 20 to 30 ms on average; this effect decreased for deliberately ''unmusical'' performances and for melody voices in the middle of a chord (Brahms op. 117/1). In a second study, melody lead was investigated exclusively (Palmer, 1996). Six pianists played the first section of Chopin's Prelude op. 28/15 and the initial 16 bars of Beethoven's Bagatelle op. 126/1 on a Bösendorfer computer-monitored grand piano (SE290, as in the current study). Again, melody lead was found to increase with intended expressiveness, also with familiarity with a piece (the Bagatelle was sight-read and repeated several times), and with skill level (expert pianists showed a larger melody lead than student pianists).

In another study published at the same time, in part with the same music, Repp (1996b) analyzed 30 performances by 10 pianists of the whole Chopin Prelude op. 28/15, a Prelude by Debussy, and ''Träumerei'' by Schumann on a Yamaha upright Disklavier. To reduce random variation, Repp averaged over the three performances produced by each pianist. He then calculated timing deviations between the (right hand) melody and each other voice, so that asynchronies within the right hand and between hands could be treated separately. He argued that melody lead could be explained mostly as a consequence of dynamic differences between melody and accompaniment. Dynamic differences (differences in MIDI velocity) were positively correlated with timing differences between the melody and each of the other voices, and these correlations were generally higher for asynchronies within the right hand than for those between hands.

Palmer (1996) also computed correlations between melody lead and the average hammer velocity difference between melody and accompaniment, but her correlations were mostly nonsignificant. In her view, the anticipation of the melody voice is primarily an expressive strategy that is used independently from other performance parameters such as intensity, articulation, and pedal use. In a perception test, listeners had to identify the intended melody in a multivoiced piece by rating different artificial versions: one with intensity differences and melody lead, one with melody lead only, and one without any such differences. Melody identification was best for the original condition (melody lead and intensity difference), but the results in the melody lead condition did not differ much from the results in the neutral condition, especially for nonpianist listeners. Only pianist listeners showed some success in identifying the intended melody from melody leads alone. A condition with intensity differences only was not included (Palmer, 1996, p. 47).

B. Piano action timing properties

To fully explain the melody lead phenomenon, it is necessary first to clarify its physical underpinnings. The temporal parameters of the piano action have been described by Askenfelt (1990) and Askenfelt and Jansson (1990, 1991, 1992). When a key is depressed, the time from its initial position to the bottom contact ranges from 25 ms (*forte* or 5-m/s final hammer velocity, FHV) to 160 ms (*piano* or 1-m/s FHV; Askenfelt and Jansson, 1991, p. 2385).[1] In a grand piano the hammer impact times (when the hammer excites the strings) are shifted in comparison to key bottom contact times. According to measurements by Askenfelt (1990, p. 43), the hammer impact time is 12 ms before the key bottom contact at a *piano* touch (hammer velocity 1 m/s), but 3 ms *after* the key bottom contact at a *forte* attack (5 m/s). The timing properties of a grand piano action are outlined by these data, but more detailed data were not available (Askenfelt, 1999, personal communication).

The timing properties of the piano action can be modified by changing the regulation of the action. Modifications, e.g., in the hammer-string distance or in the *let-off distance* (the distance of free flight of the hammer, after the jack is released by the escapement dolly) affect the timing relation between hammer-string contact and key-bottom contact (Askenfelt and Jansson, 1990). Greater hammer mass in the bass (Conklin, 1996, p. 3287) influences the hammer-string contact durations (Askenfelt and Jansson, 1990), but not the timing properties of the action.

Another measurement was made by Repp (1996b) on a Yamaha Disklavier on which the ''prelay'' function was not working.[2] This gave him the opportunity to measure roughly a grand piano's timing characteristics in the middle range of the keyboard. He measured onset asynchronies at different MIDI velocities in comparison to a note with a fixed MIDI velocity. The time deviations extended over a range of about 110 ms for MIDI velocities between 30 and 100 and were fit well by a quadratic function (Repp, 1996b, p. 3920).

The timing characteristics of electronic keyboards vary across manufacturers and are rarely well documented. Each key has a spring with two electric contacts that define the off and on states. When a key is depressed, the spring contact is moved from the off position to the on position (see Van de Berghe *et al.*, 1995, p. 16). The time difference between the breaking of the off contact and the on contact determines the MIDI velocity values; the note onset is registered near the key bottom contact.

We now have to distinguish between asynchronies at the beginning of the attack movement (finger-key contact) and asynchronies at its end (hammer-string impact or key-bottom contact). Computer-monitored grand pianos, like those of Yamaha or Bösendorfer, store time points of hammer-string impact, which are essentially equivalent to the beginnings of the sound events (see Fig. 1).[3]

II. AIMS

Almost nothing is known about asynchronies at the finger-key level, because none of the instruments used for acquiring performance data measure this parameter. However, to clarify the origin of melody lead, it is important to consider exactly those finger-key asynchronies. When pianists stress one voice in a chord, do they hit the keys asynchronously or do their fingers push the keys down at the same time but with different velocities, so that the hammers arrive at the strings at different points in time?

To examine this question, it is necessary to determine the finger-key contact times. One possibility might be to observe finger key contacts by using a video camera or by special electronic measurements at the keyboard. In this study, the finger-key contacts were inferred from the time the

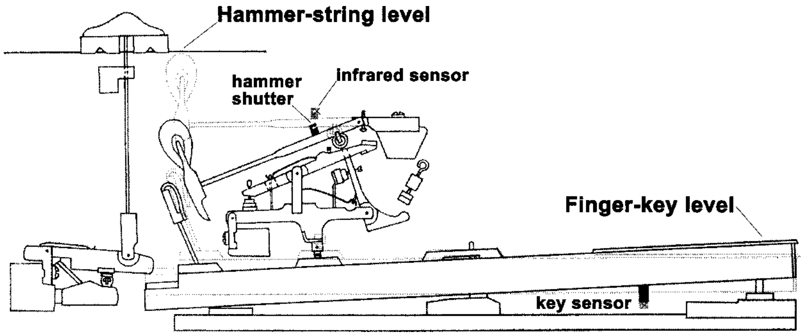

FIG. 1. Grand piano action, with the measurement points of the Bösendorfer SE system sketched. The infrared sensor mounted on the hammer flange rail captures two trip points of the shutter on the hammer shank: one 5 mm below the strings, the second immediately at the strings. The sensor at the key reacts when the key is depressed more than about 2 mm. (Figure prepared with computer software by the author.)

hammer travels from its resting position to the strings at different final hammer velocities (timing correction curve). With the help of this function, the finger-key contacts could be accurately estimated; also the size of the expected melody lead effect in milliseconds could be predicted from the velocity differences between the voices, assuming simultaneous finger-key contacts.

III. METHOD

A. Materials and participants

The *Etude* op. 10/3 (first 21 measures, Fig. 2) and the *Ballade* op. 38 (initial section, bars 1 to 45, Fig. 3) by Frédéric Chopin were recorded on a Bösendorfer SE290 computer-monitored concert grand piano by 22 skilled pianists (9 female and 13 male). They were professional pianists, graduate students or professors at the Universität für Musik und darstellende Kunst (University of Music and Performing Arts) in Vienna. They received the scores several days before the recording session, but were nevertheless allowed to use the music scores during recording. Their average age was 27 years (the youngest was 19, the oldest 51). They had received their first piano lesson at 6 and a half years of age on average. They had received piano instruction for a mean of 22 years (s.d.=7); 8 of them had already finished their studies; about half of them played more than 10 public concerts per year.

After the recording, the pianists were asked to play the initial 9 bars of the Ballade in two additional versions: first with a particularly emphasized highest voice (voice 1, see Fig. 3) and second with an emphasized third voice (the lowest voice in the upper stave, played also by the right hand, see Fig. 3). The purpose of these special versions was to investigate how pianists change melody lead and dynamic shaping of the voices when they were explicitly advised to emphasize one particular voice.

All performance sessions were recorded onto digital audio tape (DAT), and the performance data from the Bösen-

FIG. 2. Frédéric Chopin. Beginning of the Etude in E major, op. 10/3. The numbers against the note heads are voice numbers (soprano=1,...,bass=7). (Score prepared with computer software following Paderewski Edition.)

FIG. 3. Frédéric Chopin. The beginning of the second Ballade op. 38 in F major (the first 23 bars). The voices are numbered as in Fig. 2, but the highest number is now 5 for the bass. (Score prepared with computer software following Henle Urtext Edition.)

dorfer grand piano were stored on a PC's hard disk. The performances were consistently of a very high pianistic and musical level.[4] At the end of the session, the participants had to fill in a questionnaire

B. Apparatus

To provide accurate performance data, a Bösendorfer SE290 *Imperial* computer-monitored concert grand piano[5] was used. The exact recording and playback functionality of the Bösendorfer SE system is insufficiently described in the manual and literature (Moog and Rhea, 1990; Palmer and Brown, 1991; Alcedo and Schäfer, 1992; Repp, 1993; Palmer, 1996). Additional information was obtained from W. Stahnke (private communication, see Note 3) and from the Bösendorfer technician F. Lachnit.

The SE system (see Fig. 1) is equipped with two sets of shutters, one at the hammers, another one under the keys. The hammer shutters provide two trip points, one as the hammer crown just starts to contact the string and the other 5 mm lower. These two trip points capture two instants in time as the hammer travels upward, and the time difference between these instants yields an estimate of the *final hammer velocity* (FHV, in meters per second).[6]

The instant at which the trip point at the strings is passed is taken as the note onset time. The note onset times are taken 800 times per second, thus they have a timing resolution of 1.25 ms. The SE system has another set of shutters about 2–3 mm under the keys, which provides the note offset times and—only in the case of silent notes (if the hammer does not touch the strings)—notes onsets.

To avoid timing distortions in reproduction, the Bösendorfer SE290 uses a timing correction similar to the Yamaha Disklavier's ''prelay'' function (cf. Repp, 1996b). The Bösendorfer SE system recalculates the precise timing characteristics for each key individually by running a calibration program on demand. Among other parameters, the calibration function records the travel time interval from the key-shutter response (2–3 mm below key zero position) to the hammer string impact for seven final hammer velocities and all 97 keys (the Bösendorfer SE290 has 9 additional keys in the bass). This data matrix is stored in a hardware chip (EEPROM X2816AP). The memory of this hardware chip of the particular grand piano in Vienna used in the experiments was transferred into a file. The timing correction matrix (TCM) derived from these data is shown in Fig. 4. The data include both irregularities of the piano action and the electronic playback system. What can be seen from this matrix is that travel time does not depend on hammer mass which becomes greater in the bass. It seems moreover that the properties of the individual keys do not vary much in the middle range of the keyboard, except at low velocities.

After eliminating outliers that may be due to irregularities in the electronic equipment, the TCM was averaged across the keyboard. The (inverse power) curve interpolated to these seven averaged data points gave a stable representation of the travel times as a function of final hammer velocity (Fig. 5).[7]

C. Procedure

Note onsets and the hammer velocity information were extracted from the performance data. These data were matched to a symbolic score in which each voice was individually indexed, beginning with 1 as the highest voice[8] (see Figs. 2 and 3). Wrong notes (substitutions) or missing notes (deletions) were marked as such. The rate of not-played or wrongly played notes was very low: for all pianists 0.43% for the Etude (of $n_{\mathrm{total}}=9988$), 0.69% for the Ballade (of $n_{\mathrm{total}}=16\,082$), and 1.75% for the two repeated versions of the Ballade (of $n_{\mathrm{total}}=5764$).[9]

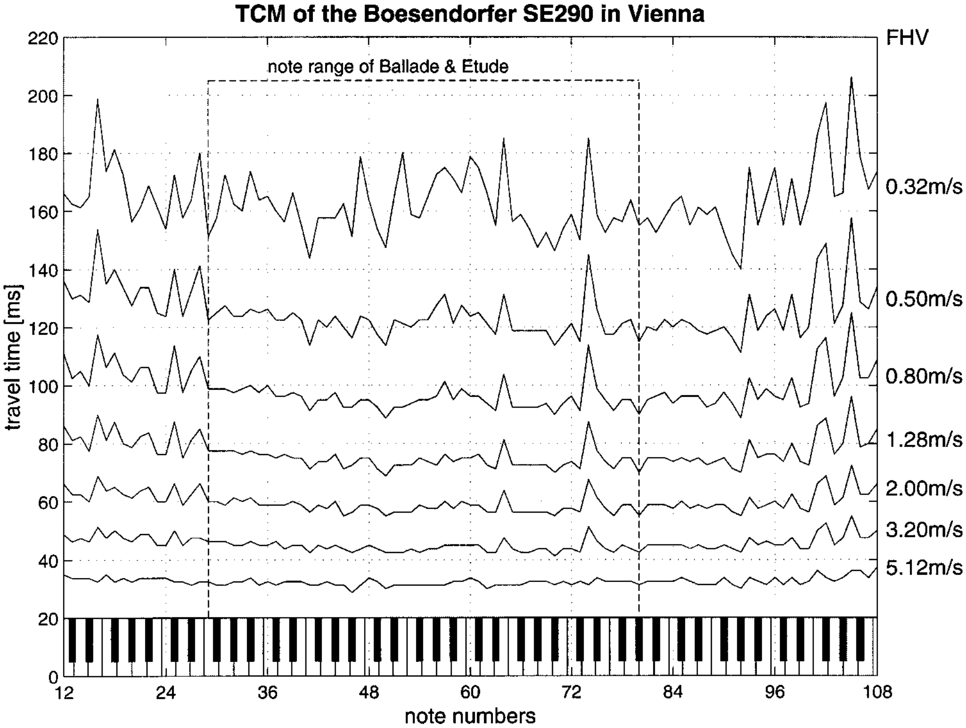

FIG. 4. The travel time correction matrix (TCM) of the Bösendorfer SE290 in Vienna used for the experiments. The seven functions display the measured travel time for seven final hammer velocities. This matrix is derived from a hardware chip (EEPROM) included in the Bösendorfer SE system.

Timing differences and hammer velocity differences between the first voice (=melody) and each other voice were calculated separately for all nominally simultaneous events in the score. All missing or wrong notes, as well as chords marked in the score as arpeggio (Ballade) or as appoggiatura (Etude) were excluded.[10] The finger-key contact times were calculated for each note by subtracting from the hammer-string impact time the corresponding travel time, which was determined by the TCC (see Fig. 5). From this, finger-key asynchronies were calculated, again between voice 1 and all other voices separately for all nominally simultaneous events in the score.

IV. RESULTS

Figure 6 shows the mean velocity profiles (top graphs) as well as the mean asynchrony profiles (bottom graphs) of the 22 performances of the Ballade and the Etude and their overall averages. All pianists played the first voice consistently louder than the other voices. None of the pianists chose another voice to be played as the loudest voice. The velocity levels of the individual voices were fairly constant in the performances of the Ballade, so averaging over all notes in a voice made sense. For the performances of the Etude the dynamic climax of bar 17 caused a strong increase in the velocity values. Therefore, in Fig. 6 the section from bar 14 to 18 was averaged separately and was not included in the overall average. Again, the first voice clearly showed the highest velocity values.

The two bottom graphs in Fig. 6 show the hammer-string and the finger-key asynchrony profiles for the two pieces. The thicker lines with the standard deviation bars represent the average of the mean asynchrony profiles of the 22 performances (thin lines without symbols).

In the hammer-string domain, the melody preceded other voices, as expected, by about 20–30 ms. In the Ballade the asynchrony profiles of the individual performances were very similar to each other, and the melody lead was slightly greater relative to the left hand voices than to the right hand voices. The individual chord profiles for the Etude showed more variability among pianists, especially in the left hand, where the bass voice (7) tended to lead for some pianists (for an example, see the following).

The asynchronies at the finger-key level (Fig. 6, broken lines, average with circles) were consistently smaller than those at hammer-string level. In particular, the melody lead within the right hand is reduced to about zero, whereas the left hand tends to lead the right hand. Two repeated-measure analyses of variance (ANOVA) on the average melody leads for each voice in each performance with type of asynchronies (hammer-string and finger-key) and voice (2 to 5 in the Ballade and 2 to 7 in the Etude) as within-subject factors separately for the two pieces (Etude, Ballade) showed significant main effects of type of melody lead and significant interactions between type and voice.[11]

A real outlier was pianist 3, who played the melody 40–70 ms before the accompaniment, as shown in Fig. 7. This was a deliberate strategy that pianist 3 habitually uses to emphasize melody. In a private communication with pianist 3, he confirmed this habit and called it a ‘‘spleen.’’ His finger-key profiles still showed a melody lead of about 20 ms and more. A similar but smaller tendency was shown by two other pianists. This finding suggests that melody lead can be applied deliberately and used as an expressive device—in addition to a dynamic differentiation—to highlight the melody. We argue here that, when melody lead is used as a conscious expressive device, it should be observable at the finger-key level. This strategy seems to be fairly rare.

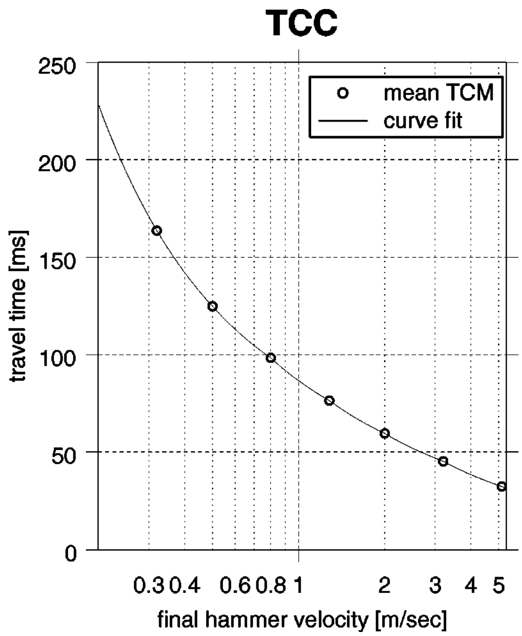

FIG. 5. The timing characteristics of a grand piano action: the hammer travel times as a function of final hammer velocity. This timing correction curve (TCC) was fitted to average data derived from a Bösendorfer SE EPROM chip (see Fig. 4). The *y* axis represents the time interval between finger-key contact times (measured 2–3 mm below the key surface) and the hammer-string contact times.

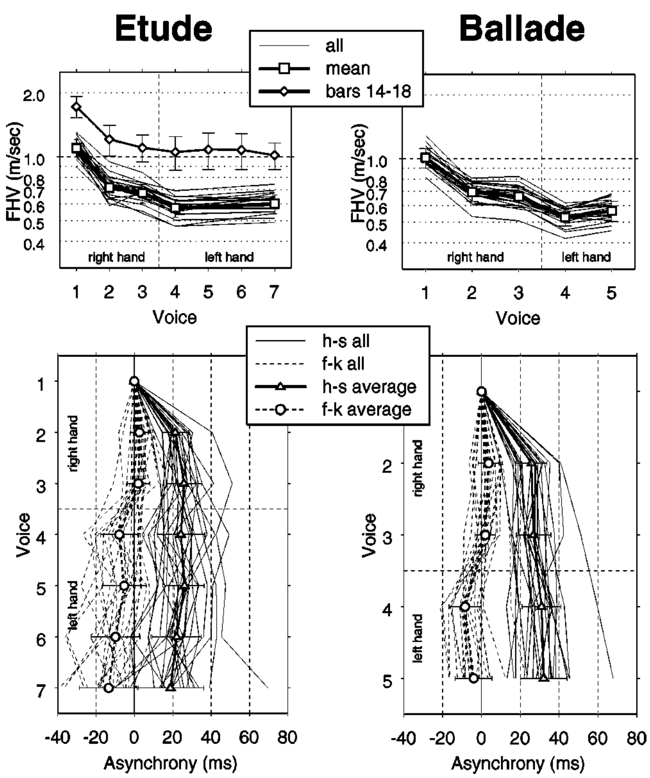

FIG. 6. The individual and mean final hammer velocity (FHV) and asynchrony profiles (with standard deviation bars) of 22 performances for the Etude (left-hand panel) and the Ballade (right). In the top panel, the mean intensity values by pianists and voice are plotted. The thicker lines with squares indicate the average across pianists. In the Etude, bars 14–18 are averaged separately. The profiles at the bottom show the averaged timing delays of voices relative to voice 1. Solid lines represent hammer-string (*hs*) asynchronies, broken lines inferred finger-key (*fk*) asynchronies. The horizontal bars are standard deviations, computed across individual performers.

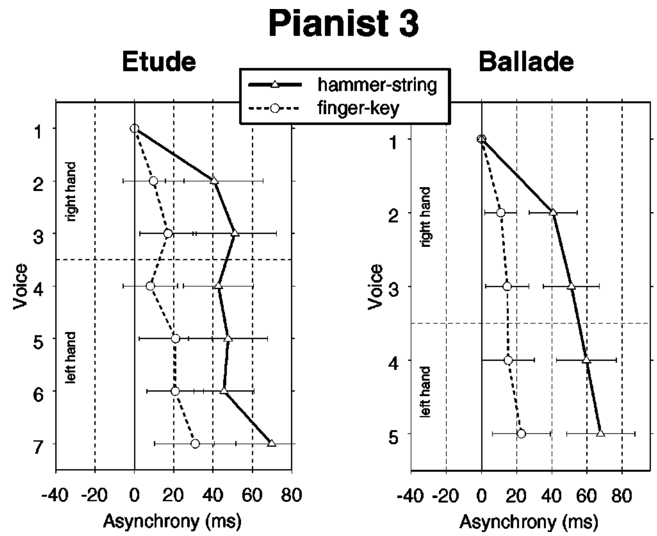

FIG. 7. The asynchrony profiles of pianist 3 (with standard deviation bars) at hammer-string contact (closed lines with triangles) and finger-key contact (broken lines with circles).

The results of the two emphasized versions of the first nine bars of the Ballade are shown in Fig. 8. In the top graphs, the mean intensity values are plotted by voices. In the first voice version (top left graph), the emphasized voice was played louder than in the normal version (mean FHV 1.28 m/s vs 1.01 m/s), while the accompaniment maintained its dynamic range. The melody lead increased up to 40–50 ms (Fig. 8, bottom left graph).

When the third voice was emphasized, that voice was played loudest (at about FHV 1.12 m/s on average), with the melody somewhat attenuated (0.84 m/s) and the other voices as usual (top right graph). The third voice led by about 20 ms compared to the first voice, while the left hand lagged by about 40 ms (Fig. 8). Thus, when pianists are asked to emphasize one voice, they play this voice louder, and the timing difference changes correspondingly.

The first nine bars of the (normal version of the) Ballade were compared with these two special versions (Ballade first voice, Ballade third voice) with regard to hammer velocity and melody lead. A repeated-measure ANOVA on the average hammer velocities of each voice in each performance with instruction (normal, first, third) and voice (1–5) as within-subject factors was conducted. Significant effects on instruction $[F(2,21)=4.98, p<0.05]$, voice $[F(4,84)=466.2, p<0.001]$, and a significant interaction between instruction and voice $[F(8,168)=88.58, p<0.001]$ indicate that pianists changed the dynamic shaping of the individual voices significantly. Another repeated-measure ANOVA was conducted on the melody leads averaged for each voice in each performance, again with instruction (normal, first, and third) and voice (2–5) as within-subjects factors. It showed significant effects of instruction $[F(2,42)=114.41, p<0.001]$ and voice $[F(3,63)=24.12, p<0.001]$, and an interaction between instruction and voice $[F(6,126)=31.29, p<0.001]$.

Relationship between velocity and timing. Generally, it was the case that the larger the dynamic differences, the greater the extent of melody lead. The velocity differences

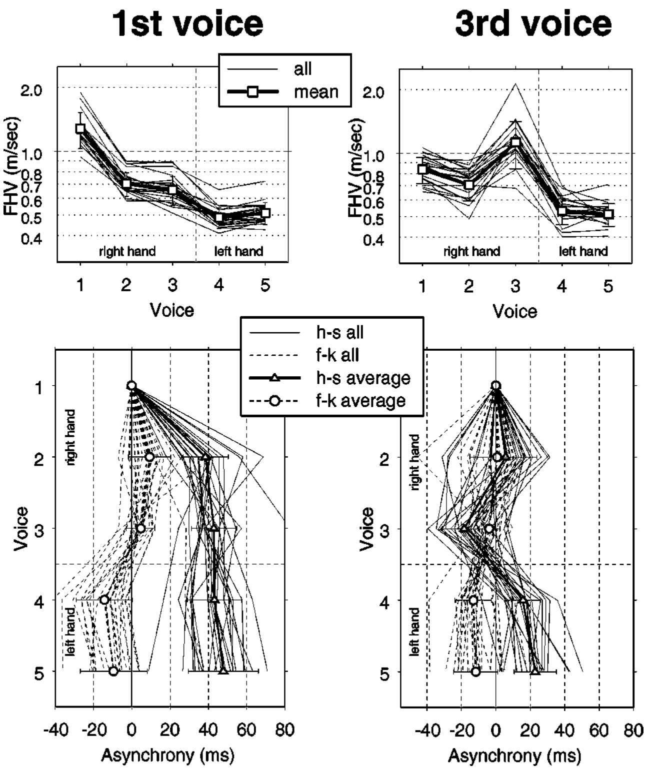

FIG. 8. Average velocity and asynchrony profiles of the 22 individual performances in the Ballade's emphasized melody conditions. On the left-hand side, the first voice was emphasized, on the right, the third voice. The solid lines indicate hammer-string (*hs*) contacts, broken lines finger-key (*fk*) contacts.

between the first voice and the other notes were negatively correlated with the timing differences. The mean correlation coefficients across the 22 pianists are shown in Table I(a), separately for each piece and for right-hand (within-hand) and left-hand (between-hand) comparisons.[12]

The within-hand coefficients were substantially higher than the between-hand coefficients. This suggests a larger independence between the hands than between the fingers of a single hand. Especially for the Etude, almost all of the between-hand coefficients were nonsignificant (with the exception of two pianists). The coefficients for the special versions were slightly higher than those for the ''normal'' versions.

These correlation coefficients assume a linear relationship between melody leads and the velocity differences. However, the expected effect resulting from the piano action timing properties (velocity artifact) does not represent a linear, but rather an inverse power relation (see Fig. 5). To test the presence of this effect in the data, the observed timing differences were correlated with the timing differences predicted by the TCC [Table I(b)]. These correlations were generally higher than the correlations between timing differences and final hammer velocity differences. Eighty-seven out of 88 individual coefficients were highly significant for the right hand. This result shows that the connection of melody lead and intensity variation is even better explained by the velocity artifact than by a linear correlation, as done in literature (Repp, 1996b; Palmer, 1996).

Some of the individual left-hand correlation coefficients between observed and predicted melody lead were nonsignificant in the Etude, but not in the Ballade or in the special versions [Table I(b)]. This suggests not only the general trend of larger between-hand asynchrony variability, but is also due to large bass anticipations—the type 2 asynchronies mentioned previously—played by some pianists, who clearly struck some bass notes earlier. To illustrate these bass anticipations, the beginning of the Etude performed by pianist 5 is shown in Fig. 9. In the bottom graph of Fig. 9, we can observe five bass leads. Two are quite small (bars 6 and 7 about 35–40 ms), two are somewhat larger (bars 2 and 8 about 75 ms) and one is huge (bar 9, 185 ms). All bass leads are even larger in the finger-key domain (see Fig. 9, open symbols). In this example, most of the large bass leads occur at metrically important events. These bass leads are well perceivable and often exceed the range of the melody leads.

V. DISCUSSION

In this study, a large and high quality set of performance data was analyzed. In addition to the measuring of asynchronies at the hammer-string impact level, we estimated the asynchronies at the start of the key acceleration (finger-key

TABLE I. (a) Mean correlation coefficients, with standard deviations (s.d.), between melody lead and final hammer velocity differences across 22 pianists. n_{max} indicates the maximum number of note pairs that went into the computation of each correlation (missing notes reduced this number at some individual performances). $\#r^{**}$ indicates the number of highly significant ($p<0.01$) individual correlations ($\#r^{**}_{max}=22$). (b) The mean correlation coefficients, with standard deviations (s.d.), between observed and predicted melody lead across 22 pianists, and the number of highly significant ($p<0.01$) correlations of the pianists ($\#r^{**}$).

	Etude		Ballade		Ballade first voice		Ballade third voice	
	right hand	left hand	right hand	left hand	right hand	left hand	right hand	left hand
(a)								
n_{max}	126	103	181	269	29	58	29	58
Mean	−0.45	−0.15	−0.42	−0.31	−0.55	−0.29	−0.73	−0.53
s.d.	0.12	0.20	0.13	0.12	0.17	0.22	0.14	0.17
$\#r^{**}$	21	2	22	20	16	12	22	18
(b)								
n_{max}	126	103	181	269	29	58	29	58
Mean	0.66	0.34	0.58	0.50	0.72	0.55	0.79	0.63
s.d.	0.10	0.23	0.13	0.13	0.17	0.22	0.11	0.13
$\#r^{**}$	22	14	22	22	21	21	22	22

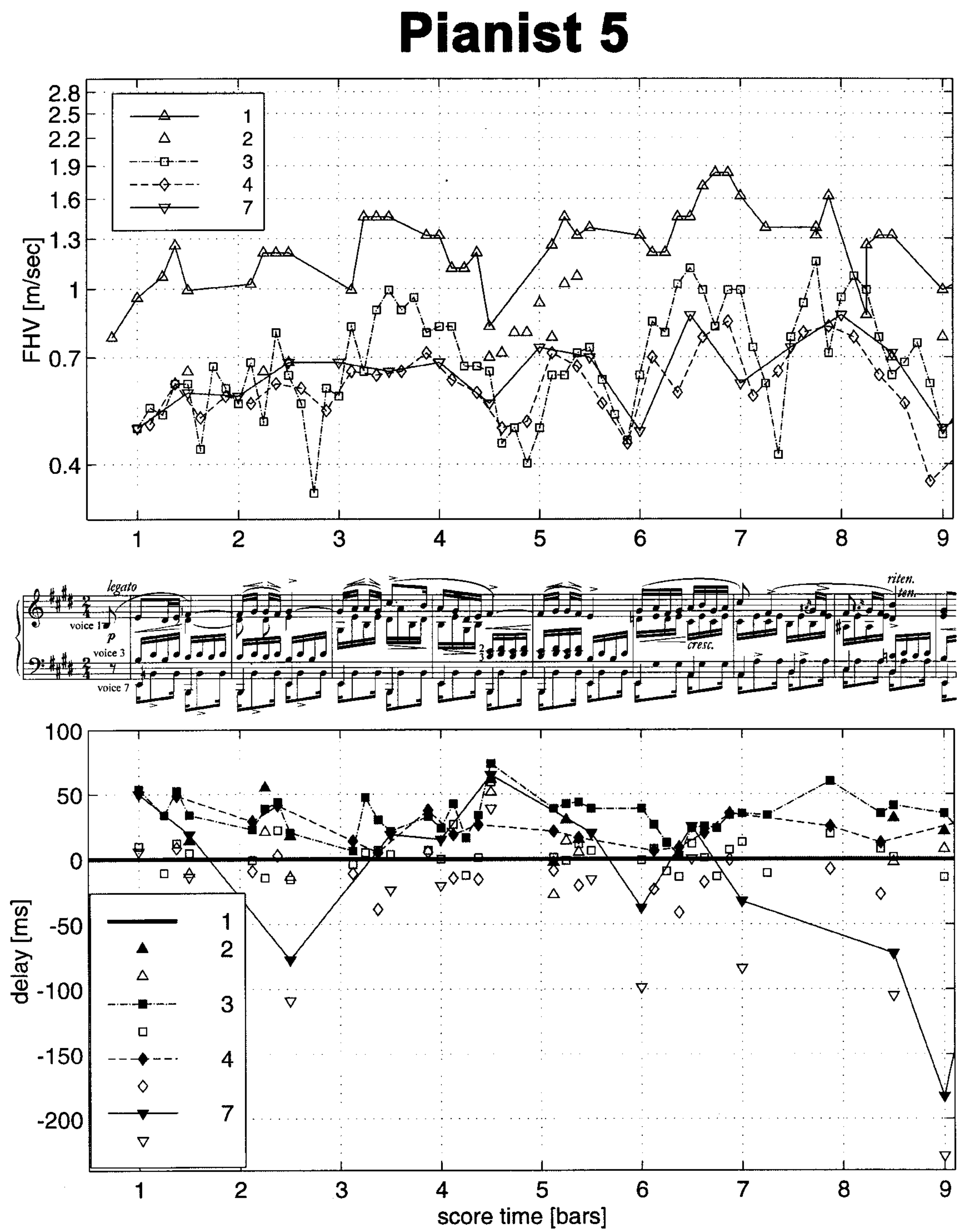

FIG. 9. The dynamic profiles (top) and the note asynchronies (bottom) for the first bars of the Etude op. 10/3 for pianist 5. Top graph: The final hammer velocity (FHV) is plotted against nominal time according to the score. Each voice is plotted separately. The melody is played clearly more loudly than the other voices. The bottom graph shows the time delay of each note relative to onset time of the corresponding melody note (voice 1). The closed symbols represent hammer-string asynchronies, the open symbols the estimated finger-key contact times.

level) through calculation. The hypothesis that melody lead occurs as a consequence of dynamic differentiation was supported in three ways.

(1) The consistently high correlations between hammer-string asynchronies and dynamic differences show the overall connection of melody and velocity difference. The more the melody is separated dynamically from the accompaniment, the more it precedes it. These findings replicate Repp's (1996b) results.

(2) In addition to these findings, the estimated finger-key asynchronies show that, with few exceptions, the melody lead phenomenon disappears at finger-key level. Pianists start to strike the keys almost synchronously, but different velocities cause the hammers to arrive at the strings at different points in time.

(3) With the help of the timing correction curve (TCC), melody lead was predicted in ms. The correlations between this predicted and the observed melody lead were

even higher than the correlations between velocity differences and melody lead. Differences in hammer velocity account for about half of the variance in asynchronies in the data. The other variance could be due to deliberate expression, or motor noise.

The findings of this study are consistent with interpretations of Repp (1996b, velocity artifact explanation) rather than those of Palmer (1989, 1996), who regarded melody lead to be produced independently of other expressive parameters (e.g., dynamics, articulation). Of course it remains true that melody lead can help a listener identify the melody in a multivoiced music environment. Temporally offset elements tend to be perceived as belonging to separate streams (*stream segregation*, Bregman, 1990), and spectral masking effects are diminished by asynchronous onsets (Rasch, 1978, 1979). But in light of the present data, perceptual segregation is not the main reason for melody lead. Primarily, the temporal shift of the melody is a result of the dynamic differentiation of the voices, but both phenomena have similar perceptual results, that is, separating melody from accompaniment.

Nevertheless, pianists clearly played asynchronously in some cases. Some bass notes are played before the melody. Bass lead time deviations are usually around 50 ms and extend up to 180 ms in some cases. These distinct anticipations seem to be produced intentionally, although probably without immediate awareness. This bass lead is well documented in the literature, not only as a habit of an older pianists's generation, but also in some of today's young pianists' performances (Repp, 1996b; Palmer, 1989).

The case of pianist 3 suggests that pianists can enlarge the melody lead deliberately if they wish to do so. In this case, even in the finger-key domain melody lead is observable. However, it does not seem possible for pianists to dynamically differentiate voices in a chord without producing melody lead in the hammer-string domain. At least there is no example in the present data that would prove this.

In the examples of deliberately produced asynchronies (bass lead and enlarged melody lead), the extent of the asynchrony usually exceeded 30 ms. Such asynchronies may be regarded as a deliberate expressive device under direct control of the pianists. According to the pianists in this study, they are produced in a somewhat subconscious way (private communication with the pianists), but pianists report a general awareness of the use of these asynchronies and that they could suppress them if they wanted to. However, the use of the ''normal'' melody lead that was produced by *all* pianists was unconscious. Pianists reported that they emphasize one voice by playing it dynamically louder, but not earlier (the same was reported by Palmer, 1989, p. 335).

The asynchronies in the finger-key domain were computed by using a timing correction curve which provides the time interval from key-press to hammer-string impact as a function of final hammer velocity. The key shutter reacts when the key is depressed about 2 to 3 mm (the ''touch depth'' of the key is usually about 9.5 mm, Askenfelt and Jansson, 1991, p. 2383, varying slightly across pianos). Thus, to be precise, the finger-key domain represents points in time when keys are depressed by 2 to 3 mm. However, almost nothing is known about how keys are accelerated and released in reality. In very precise acceleration measurements by Van den Berghe (Van den Berghe *et al.*, 1995, p. 17) it can be seen that sometimes keys are not released entirely, especially in repetitions. The modern piano action has the double repetition feature that allows a second strike without necessarily releasing the key entirely. If the system measured onsets close to the zero position, some onsets would not be detected as such. Nevertheless, the 2 to 3 mm below zero level still gives a good impression about the asynchronies at the start of a key acceleration. For more accurate statements about played and perceived onset asynchronies in piano performance, evaluation of acceleration measurements at different points in the piano action would be necessary.

This paper was concerned with the particular properties of the piano. Other keyboard actions (harpsichord, organ) may have similar timing properties as far as the key itself is concerned (a key that is depressed faster reaches the keybed earlier than a slower one), but their actions respond differently due to their different way of producing sound: the harpsichord plucks the strings, and on the organ a pipe valve is opened or closed. Additionally, they do not allow continuous dynamic differentiation like a piano does, and therefore performers may choose timing as a means to separate voices. However, we note a difference in the played repertoire: homophonic textures, like the Chopin excerpts used in this study, are seldom seen in the harpsichord or organ repertoires.

According to Vladimir Horowitz, when accenting a tone within a chord one should ''raise the whole arm with as little muscular effort as possible, until the fingers are between three and five inches above the key. During the up and down movements of the arm, prepare the fingers by placing them in position for the depression of the next group of notes and by holding the finger which is to play the melody-note a trifle lower and firmer than the other fingers which are to depress the remaining keys of the chord'' (Eisenberg, 1928).[13] This would suggest that an asynchrony at the key is intended, but Horowitz goes on: ''The reason for holding the finger a trifle lower is only psychological in effect; in actual practice, it isn't altogether necessary. Experience shows that in the beginning it is almost impossible to get a student to hold one finger more firmly than the others unless he is also permitted to hold it in a somewhat different position from the others. Holding it a little lower does not change the quality or quantity of tone produced and does not affect the playing in any way but it does put the student's mind at greater ease'' (Eisenberg, 1928). As the pianists in the present study, Horowitz is aiming at intensity differences here, but not at differences in timing: ''The finger which is held a trifle lower and much firmer naturally strikes the key a much firmer blow than do the more relaxed fingers which do not overcome the resistance of the key as easily as does the more firmly held finger. The tone produced by the key so depressed is therefore stronger than the others'' (Eisenberg, 1928). The quote suggests that Horowitz was unaware of the consequences of his recommendation for onset synchrony or that he considered onset asynchrony unimportant.

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[1]Askenfelt and Jansson (1990) used a Hamburg Steinway & Sons grand piano, model B (7 ft, 211 cm) for their measurements.

[2]The ''prelay'' function compensates for the different travel times of the action at different hammer velocities. In order to prevent timing distortions in reproduction, the MIDI input is delayed by 500 ms. The solenoids (the linear motors moving the keys) are then activated earlier for softer notes than for louder notes, according to a pre-programmed function.

[3]Palmer's (1996, pp. 27 and 29) assumption that the Bösendorfer SE290 grand piano records key-bed impact times as note onsets is contradicted by information given by W. Stahnke (private communication), who developed the SE system in the 1980s (Moog and Rhea, 1990, p. 53),

[4]All recordings can be downloaded in MP3 format at *http://www.ai.univie.ac.at/~wernerg*

[5]''SE'' stands for Stahnke Electronics, 290 indicates the length of the piano in cm.

[6]This time difference is by definition called the *inverse hammer velocity* (IHV), and is measured by a counter operating at 25.6 kHz. Therefore, the relationship between the *IHV* and the *final hammer velocity*, expressed in meters per second, is determined via the function IHV=128/FHV. The IHV values can range from 0 (128 m/s) to 1023 (0.125 m/s). The performing pianists typically produce IHV values between 30 (4.26 m/s) and about 600 (0.21 m/s), where at 600 the hammers will not reach the strings anymore (silent note).

[7]In an earlier analysis (Goebl, 2000), the author made use of average TCM data provided by Stahnke (private communication), derived from his Bösendorfer SE290. It was preferred in the present study to use the mean TCM from the Vienna SE grand. However, the differences between these two inverse power curves were very small and did not affect the results much.

[8]The lowest voice played by the right hand was called 3. If there were three simultaneous notes in the right hand, the middle one was labeled 2. The highest voice played by the left hand was indexed 4, the base line 5 in the Ballade, and 7 in the Etude. Voices 5 and 6 in the Etude occurred only in measures 16 and 17. In the Ballade, there was only one chord (bar 19) with three simultaneous notes in the left hand. Here, the two higher notes were labeled 4, the bass 5.

[9]Additional notes (insertions) that were so soft (or silent) that they did not disturb the performance and were apparently not perceived as mistakes, were not counted as errors. In the Etude we observed 181 such notes over the 22 performances (+1.8%), in the Ballade 189 (+1.17%). Similar observations were made also by Repp (1996a).

[10]The excluded events for the Etude were ([bar number]·[relative position in the bar]): 7.75, 8.25, and 21.0, for the Ballade: 18.5, 20.5, 40.0, and 45.0.

[11]The repeated-measure ANOVA for the Ballade: significant effect of type $[F(1,21)=718.2, p<0.001]$, no significant effect of voice $[F(3,63)=1.2, p>0.05]$, and a significant interaction between type and voice $[F(3,63)=112.3, p<0.001]$; for the Etude: significant effects of type $[F(1,21)=603.9, p<0.001]$, and voice $[F(5,105)=5.59, p<0.002]$, and an interaction between type and voice $[F(5,105)=34.83, p<0.001]$.

[12]The negative sign of the correlation coefficients stems from the way of calculating timing and velocity differences and has no relevance for data interpretation: from the onset time of each accompanying note (t_n) the onset time of the corresponding melody note (t_1) is subtracted (t_n-t_1), so the melody lead is positive. Similarly, the velocity differences are calculated as: v_n-v_1, which results in negative values. Therefore, the correlation coefficients between melody leads and velocity differences are negative, whereas the coefficients between observed and predicted melody leads are positive.

[13]This article may be found at *http://users.bigpond.net.au/nettheim/horo28.htm*

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