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Pedal Timing and Tempo in Expressive Piano Performance: A Preliminary Investigation

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Abstract

The timing of pedal depressions and releases was measured relative to key depressions and releases in two pianists' performances of Robert Schumann's *Träumerei* on an electronic instrument. Each pianist provided nine complete performances, three at each of three tempi, which were analysed by examining in detail those positions in the music in which the pedal was used consistently. The principal questions were whether and how pedal timing adjusts to changes in *global tempo* (across performances) and in *local tempo* (within performances): Do pedal-release times, onset times, or change (onset minus release) times exhibit *absolute or relative invariance* across either or both of these tempo changes? The results do not suggest any simple answer, since neither type of invariance was observed consistently. Pedal timing emerges as having a complex pattern that is sensitive to local and global tempo changes in varying degrees, yet exhibits consistency across repeated performances by the same pianist. There were striking differences in pedal timing between the two pianists, who differed in level of skill.

Introduction

Modern pianos have two or three pedals, the most important of which is the *damper pedal*, referred to simply as "pedal" here. When depressed, it raises all dampers, so that the strings vibrating at that time continue to vibrate until the pedal is raised or until the vibrations decay naturally. It also enables other strings to vibrate sympathetically, thus enriching the timbre of the sustained sounds. Once the basic skill of hand–foot co-ordination has been mastered by a piano student, pedalling becomes a subconscious, automatic activity for most players. Concert pianists and teachers naturally examine and refine their pedalling skills using auditory feedback to guide them, and great artists often exhibit a masterful pedalling technique which contributes to their characteristic "tone" and "touch". Interestingly, as Heinlein (1929a) has observed, listeners tend to attribute the sonic consequences of pedalling to the pianist's manual skill, being unaware of how crucially piano performance depends on what the right foot is doing.

Piano scores often indicate when the pedal should be depressed and when it should be released. Just as often, composers and editors omit pedalling instructions from the score or insert them only at crucial points. Typically, a pianist pedals much more frequently than is indicated in the score. One common use of the pedal is to create smooth transitions between tones or chords that are difficult or impossible to connect by fingering alone. These transitional uses of the pedal (also referred to as syncopated or *legato* pedalling) are rarely notated and are at the pianist's discretion. The present study focuses on this type of pedalling.

For the psychologist interested in the cognitive and kinematic processes involved in music performance, pedalling raises interesting questions about motor control, co-ordination, and the rôle of auditory feedback, and it offers an opportunity to study an important component of pianistic skill about which rather little is known from a scientific perspective. Qualitative and quantitative aspects may be distinguished: *pedal use* and *pedal timing*, respectively. Musical notation conveys only instructions about pedal use, if any, and observation of pianists (including self-observation) with the naked eye and ear similarly yields only qualitative information. Empirical questions about pedal use concern the relative frequency with which pianists depress the pedal in a given piece of music, where in the music they use it (and why), and when they depress and release the pedal relative to the notated musical events (described in qualitative terms such as before, after, and between). In contrast, the precise timing of pedal actions is an aspect of the *expressive microstructure* of music performance (Clynes, 1983), whose measurement requires special instrumentation. Questions about pedal timing concern the detailed temporal relations between hand and foot actions, as measured by the exact times elapsing between key and pedal depressions, as well as the timing of successive foot actions: Are these intervals invariant or context-dependent? Do they stretch and shrink with changes in tempo? Do pianists differ in their pedal timing characteristics? Can pedalling skill be measured objectively? The basic technology to address these questions has been available for some time (*e.g.*, Heinlein, 1929b; Seashore, 1938), but pedal timing has been little investigated. The recent proliferation of MIDI technology, however, greatly facilitates such studies.

The only systematic studies of pedalling in the psychological literature known to this author were conducted by Heinlein (1929b, 1930) and recently by Taguti, Ohgushi, and Sueoka (1994). Heinlein (1929b) compared pianists' pedalling patterns in a qualitative way, by counting the number of times the pedal was depressed and by examining rough graphs (kymograms) of pedal actions relative to the onsets of the musical tones. He pointed out large differences in pedal use among different pianists playing the same music and considerable variability in pedalling even in the same pianists' repeated performances of the same music (*cf.* also Banowetz, 1985: p. 9). Heinlein (1930) asked four pianists to pedal while playing, tapping, listening to, or imagining the same music. He found that it is virtually impossible to produce a good pedalling pattern without actually playing the music. This confirms a point made in many discussions of pedalling in the pedagogical literature, namely that it is "governed by the ear" (see, *e.g.*, Marek, 1972; Neuhaus, 1973; Newman, 1984; Philipp, 1984; Banowetz, 1985). The recent study by Taguti *et al.* (1994), based on eight pianists' performances of a Chopin Waltz in three expressive styles, did not focus on the pedalling patterns as such but rather on the multidimensional structure of their dissimilarities and its relationship to verbal descriptions of performance quality. At this time, no detailed study of pedal timing has been reported in the literature.

To explain how pedal timing was measured in the present study, Figure 1 schematically illustrates a typical *legato* pedalling pattern in terms of MIDI events. Two successive *legato* melody notes are shown symbolically, and a relatively slow tempo is assumed, allowing the player to pedal with each individual note if (s)he so wishes. The "note on" events (which closely coincide with the acoustic onsets of the tones represented by the notes) define a physical *interonset interval* (IOI) within which pedal events may be located. In *legato* pedalling, a pedal depression ("pedal on") typically precedes a key depression ("note on"), and a

pedal release ("pedal off") follows it. Thus the pedalling serves to prolong the duration of the *preceding* tone whose key release ("note off") may occur before or after the onset of the following tone, but nearly always before the pedal is released; thus the *legato* connection of the tones is enhanced by the prolongation afforded by the pedalling. (If the key release *follows* the pedal release, the pedalling is redundant with regard to the achievement of *legato* articulation but adds richness of timbre.) This pedal action is repeated for the next tone, and so on. Within an IOI defined by two key depressions, then, there are typically two pedal events: a release followed by a depression. This rapid sequence of foot actions is known as a *pedal change*.

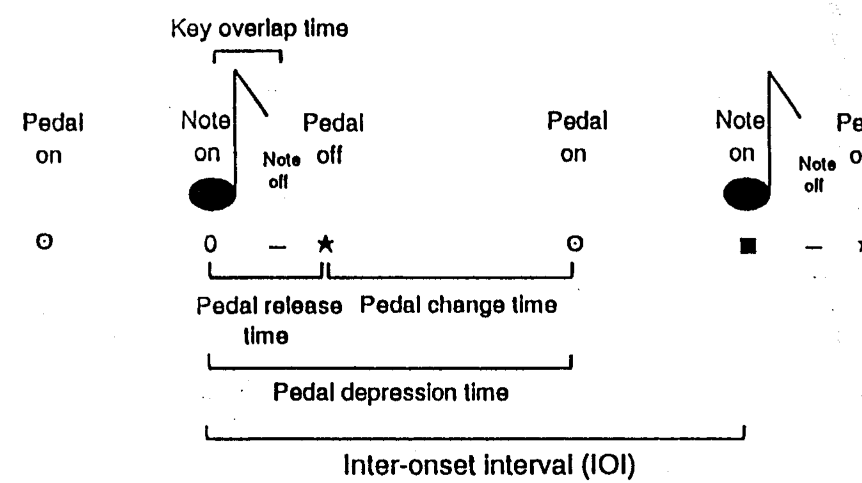

FIG. 1

Schematic illustration of MIDI events and temporal intervals in a typical *legato* pedalling pattern. The symbols are the ones that will be used in later data graphs (Figs. 6–7). The first "note on" corresponds to time zero.

Three time intervals will be of particular interest in this study (see Fig. 1). The first is the temporal location of a pedal release within an IOI, referred to as *pedal release time* (PRT). The second is the location of a pedal depression within an IOI, referred to as *pedal depression time* (PDT). The third is the interval between a pedal release and a pedal depression, provided that both occur within (or very nearly within) the same IOI; it will be referred to as *pedal change time* (PCT). Each of these three intervals can be specified in *absolute* terms, in milliseconds, or in *relative* terms, as a percentage of the IOI in which it occurs (PRT%, PDT%, PCT%).

Because pedalling depends on what the hands are doing, it seems that it must be *rhythmically co-ordinated* in some fashion with the manual actions. The nature of this co-ordination would be most easily investigated when all successive IOIs are equal in duration, as might be the case in simple exercises carried out in a mechanical fashion. The present study, however, focuses on the more complex but also more ecologically valid situation of expressive music performance in which IOI duration is highly variable (see, *e.g.*, Repp, 1992). The duration of a given IOI depends on three factors: (1) the note value specified in the score, (2) the *global tempo*, and (3) *local tempo* (expressive timing, agogic variation). The first factor played no rôle in the present study, as all IOIs examined corresponded to eighth notes (half beats) in the score. Attention thus focused on the second and third factors. Global tempo accounts for systematic differences in the duration of the same IOI across performances played at different tempi; local tempo accounts for systematic differences among different IOIs within the same performance. Variations in local tempo are largely governed by structural factors (hierarchical grouping, melodic contour, harmony, etc.), whereas global tempo is structure independent. Given that IOIs vary in duration due to these two sources, the theoretical question addressed in this study was *how pedal timing adjusts to these variations*.

The relative precision of pedal timing is unknown at present. It could be that pedal timing (like pedal use) is highly variable, unlike tone onset timing, which is controlled very precisely and is highly replicable across repeated performances of the same music (see, *e.g.*, Seashore, 1938; Shaffer, 1981; Shaffer, Clarke and Todd, 1985; Repp, 1992). Replicability of pedal timing patterns across repeated performances at the same tempo is a prerequisite for the investigation of systematic adjustments to tempo changes. Such adjustments may take either (or neither) of two forms: *absolute invariance* or *relative (relational) invariance*. Absolute invariance would hold if pedal releases and/or depressions always followed tone onsets by a fixed interval, or if pedal change times were approximately constant, regardless of the duration of the IOI within which these events are situated. The possible absolute invariance of pedal change times in particular seemed an interesting hypothesis, given the ubiquity, rapidity, and automaticity of the release-depression action sequence. These absolute invariance hypotheses may be contrasted with the corresponding relative invariance hypotheses, according to which some or all of the intervals mentioned stretch and shrink proportionally with changes in IOI duration.* Proportional changes in timing microstructure with changes in global tempo have been observed in many other skilled motor behaviours, at least to a first approximation (see Gentner, 1987; Heuer, 1991). Finally, it is possible that neither of these simple hypotheses applies, and that adjustments of pedal timing to changes in manual timing are more complex, but nevertheless systematic. It is also conceivable that a given temporal interval (pedal release time, say) is absolutely invariant across global tempo changes but relationally invariant across local tempo changes.

The hypothesis of absolute invariance has some plausibility because the acoustic decay characteristics of piano tones do not change with tempo. If the purpose of pedalling is to "catch" a tone at a certain dynamic level and prolong it, pedal

*Several comments are in order: (1) Relative invariance of absolute durations (in ms) is the same as absolute invariance of relative durations (percentages or proportions). (2) While the three intervals considered may be all absolutely invariant or all relationally invariant, certain other combinations are impossible; *e.g.*, absolute invariance of PCTs together with relational invariance of PRTs implies that PDTs cannot exhibit either type of invariance (PDT = PRT + PCT). Of course, most of these conceivable "mixed" scenarios are theoretically implausible. (3) Absolute and relative invariance are the easier to distinguish the later in the IOI the relevant pedalling event occurs, because early in the IOI the absolute effect of a proportional adjustment to IOI duration may be vanishingly small.

depression times may well be insensitive to changes in tempo. However, a pianist must also avoid depressing the pedal when tones that should not be prolonged are still sounding. For that reason, pedalling is likely to be sensitive not only to the timing of key depressions (which served as temporal reference points in this study) but also to that of key releases. Piano tones do not cease immediately following key release but decay over a few hundreds of milliseconds, with low tones decaying more slowly than high tones (Repp, 1995). This decay places a constraint on pedal depression times, and if key release times vary with tempo, so may pedal depression times.

The time between the key depression for one tone and the key release for the preceding tone will be referred to as *key overlap time* (KOT); it is positive when there is overlap (as in Fig. 1) and negative when there is a gap. Gaps are usually bridged by pedalling and thus are inaudible. They may occur when it is difficult to connect two tones with the fingers, but also in other places, as finger *legato* is not strictly necessary when there is *legato* pedalling. However, when finger *legato* is possible, it is commonly maintained even when the pedal is being used; the resulting key overlap time can be considerable and may vary with structural factors. For example, two consonant tones may be overlapped more than two dissonant tones, and the following pedal change may be correspondingly delayed. Thus, factors influencing overlap time may also influence pedal timing. For this reason, some key overlap times were also measured in the present study.

Finally, individual differences in pedal timing were of interest, as previous studies (Heinlein, 1929b; 1930) had focused only on individual differences in pedal use. Differences in pedal timing among pianists may reflect differences in motor organisation responsible for differences in "tone" and "touch", as well as differences in level of technical skill.

These various issues were examined in MIDI data obtained from 18 integral performances of Robert Schumann's well-known piano piece, *Träumerei* (op. 15, No. 7), which have been the subject of two previous studies by this author (Repp, 1994a; 1994b). They derive from two pianists, each of whom played the piece three times at each of three different global tempi. Repp (1994a) addressed the question of whether expressive timing patterns (*i.e.*, IOI durations) expand and contract proportionally with changes in global tempo (*i.e.*, whether they show relational invariance) or whether they change in a more complex way. (Of course, absolute invariance is impossible in this case.) Some small but statistically significant deviations from relational invariance were noted, and Desain and Honing (1994) have reported larger deviations from relational invariance in a different piece of music. For the present purposes, it is sufficient to note that variations in global and local tempo were reasonably independent in the performances studied, as was re-confirmed in the statistical analyses reported below.

Although Repp's (1994a) study focused primarily on tone interonset intervals, it also included a selective analysis of pedal timing, restricted to eight recurrences of one particular IOI in the musical structure which always contained a pedal change (bar 1-1 and corresponding locations, which represents a quarter-note IOI; see Fig. 2). These data were not very clear with regard to the two invariance hypotheses, but they revealed striking individual differences between the two pianists, both in pedal timing and in its sensitivity to tempo variation. The purpose of the present study was to analyse the pedal timing data from these performances in more detail, so as to examine more thoroughly the influence of tempo changes on the timing of hand-foot coordination in expressive piano performance. The present study was *not* concerned with providing a detailed explanation of pedal use and timing as such, *i.e.*, with accounting for why and how the pedal was deployed at particular points in the music, though some pertinent comments will be made. The primary focus was on the sensitivity of the pedal timing pattern (whatever it happened to be) to changes of tempo.

Each pianist's data were analysed separately. Based on an initial analysis of pedal use, sets of structurally similar points in the music ("vertical slices", *cf.* Fig. 2) were selected where the pedal was changed consistently. Six such sets were analysed, capturing about half of all pedalling events. By conducting statistical analyses within structurally relatively homogeneous sets, variation in local tempo was to some extent dissociated from structural variation in the music, though even within-set variation in local tempo, to the extent that it was not random or idiosyncratic, presumably was still determined by structural features of the music. Within each analysis set, the effects of global tempo and of local tempo, as well as their interaction were assessed for each of the several temporal intervals of interest. In all these repeated-measures ANOVAs, the error term for each effect of interest was its variation across performances *with the same global tempo*. In that way, across-performance stability provided the criterion for assessing the statistical reliability of any effect. Analyses were performed both on absolute and relative measures of pedal timing (PRT, PDT, PCT; PRT%, PDT%, PCT%): If an absolute interval does not vary with (global or local) tempo but the corresponding percentage does, the absolute invariance hypothesis is supported. If the opposite result is found, the relational invariance hypothesis is supported. If neither measure shows a significant effect, the results are inconclusive; high variability may be to blame. If both show a significant effect, some more complex type of tempo adjustment is suggested. No statistical comparisons were conducted between the six analysis sets, which represented different positions in the musical structure.

Method

The music

The score of Schumann's *Träumerei* is shown in Figure 2, laid out on the page so that structurally similar parts are aligned vertically. Since the first 8 bars are repeated, the music comprises 24 measures. There are three 8-bar sections (the general form is A-B-A'), each of which contains two 4-bar phrases. The predominant note value is the eighth note; thus most IOIs are nominally equal, though their actual durations varied dramatically, due to expressive timing (see Repp, 1994a). For a more detailed discussion of the music and its structure, see Repp (1992).

Pianists

Two pianists provided the performances: LPH, a professional musician in her mid-thirties, and BHR, the author, a serious amateur in his late forties. Both pianists were thoroughly familiar with the music and had played it many times before. Although BHR was capable of playing the piece accurately, consistently, and with good expression (*cf.* Repp, 1994a), his technical skills were clearly much less developed than LPH's; this was expected to be reflected in the pedal timing data.

FIG. 2

Score of Robert Schumann's *Träumerei* (No. 7 from *Kinderszenen*, op. 15). The computer-generated score follows the Clara Schumann edition (Breitkopf and Härtel), except for some minor deviations due to software limitations. The page layout helps clarify the musical structure.

Recording procedure

The recording procedure is described in detail in Repp (1994a; 1994b). The instrument was a Roland RD-250s digital piano with weighted keys and DP-2 foot-pedal switch. Although this simple pedalling device did not permit degrees of pedal depression and did not simulate sympathetic string vibration, it was nevertheless believed that the pianists' habitual pedalling patterns would be transferred to the electronic instrument, perhaps with some automatic adjustments to its acoustic characteristics (as would also occur with any unfamiliar acoustic piano). The digital piano was connected to a microcomputer which stored the performances in MIDI format (note on and off times, key velocities, and pedal on and off times), with a temporal resolution of 5 ms. The pianists monitored the sound ("Piano 1") over earphones. Each pianist played the piece 3 times at each of 3 aesthetically acceptable tempi, called "slow", "medium", and "fast" in the following. Each tempo was cued by a metronome, which was turned off before the performance started. (See Repp, 1994b, for the exact metronome settings and observations on the pianists' relative accuracy in following them.) The performances within each tempo category naturally differed somewhat in global tempo, but those differences were small relative to the differences between tempo categories.

Analysis

Following an initial analysis of qualitative pedal usage, six "vertical slices" were taken through the score, each yielding eight structurally identical or similar positions, four bars apart and referred to by bar and eighth-note numbers (*e.g.*, 13-1 denotes the first eighth-note in bar 13). In computing IOIs, whenever several tone onsets coincided nominally but their exact onset times were not identical (as is usually the case), the onset time of the tone with the highest pitch was taken as the reference. Pedal release and depression times within these IOIs were measured, and if there were two pedal events within the IOI, typically a release followed by a depression, the pedal change time was also calculated. Furthermore, the key release time of the preceding melody tone was determined if it fell within or close to the onset of the IOI. All these temporal measures were expressed both in milliseconds and as percentages of the total IOI. Within each analysis set (vertical slice through the score), each of these absolute and relative values was subjected to a mixed-model ANOVA, separately for each pianist, with the fixed factors of (global) tempo (three levels) and position (*i.e.*, local tempo; eight levels, or fewer when there were missing data), and performances (three levels, nested within tempo categories) as the random factor. Because a very large number of F values was computed, they will not be reported in detail. The statistical results are summarised in tabular form after a descriptive presentation of selected data.

Results and Discussion

Pedal use

Table 1 shows the total frequencies of pedal use in the nine performances by each pianist. Each frequency represents a pair of events: pedal depression followed by pedal release (regardless of the interval in between). It is evident that LPH used the pedal more often than did BHR. Both pianists show a tendency of using the pedal less frequently as the tempo increased. However, due to variability within each tempo category, this tendency was not significant. Heinlein (1929b) compared two famous pianists' highly divergent pedalling in the same music; their total frequencies were 51 and 135, respectively. The present counts fall between these two extremes.

TABLE 1
Frequencies of pedal use in the 18 individual performances.

Tempo	*Perf*	*LPH*	*BHR*
Slow	1	88	74
	2	93	73
	3	91	69
Medium	1	98	75
	2	87	68
	3	82	75
Fast	1	85	67
	2	92	67
	3	81	66

The detailed distribution of pedal usage throughout the music is shown in Figures 3 (LPH) and 4 (BHR). The layout of these figures matches that of the score in Figure 2. The frequencies plotted are summed over the nine performances of each pianist; for bars 1-8, moreover, the data have also been summed over the within-performance repeat, so that there were 18 renditions altogether. The white and black bars represent the frequency of pedal releases and depressions, respectively, within the IOI starting on the half-beat indicated on the abscissa. The quarter-note IOI associated with the initial upbeat of the piece (bar 0), which usually contained the first pedal depression, is omitted in these figures. (The initial depression frequencies are the complement of the release frequencies in bar 1-1.) It should be noted that the temporal order of pedal releases and depressions *within* each IOI is not represented in these figures. In the vast majority of cases, they followed the pedal change (off–on) pattern (as suggested by the relative placement of the bars in Figures 3 and 4), but there were instances of depressions preceding releases within IOIs in BHR's data.

A number of things can be observed in these figures. First, it is clear that the pedal was used much more frequently than prescribed in the score (Fig. 2). Second, each pianist showed places where (s)he used the pedal in all performances (*i.e.*, where the bars in the figure reach maximum height), whereas in other places the pedal was used less consistently. The two pianists' within-performance consistency may be gauged by comparing bars 1-4 (panel 1) with bars 17-20 (panel 5), which represent the identical music, and bars 9-12 (panel 3) with bars 13-16 (panel 4), which are very nearly transpositions of each other. BHR was somewhat more consistent than LPH by that comparison. Third, while there are similarities in pedal use between the two pianists, there are also many differences. The most striking difference is that LPH used the pedal change pattern all the time, so that

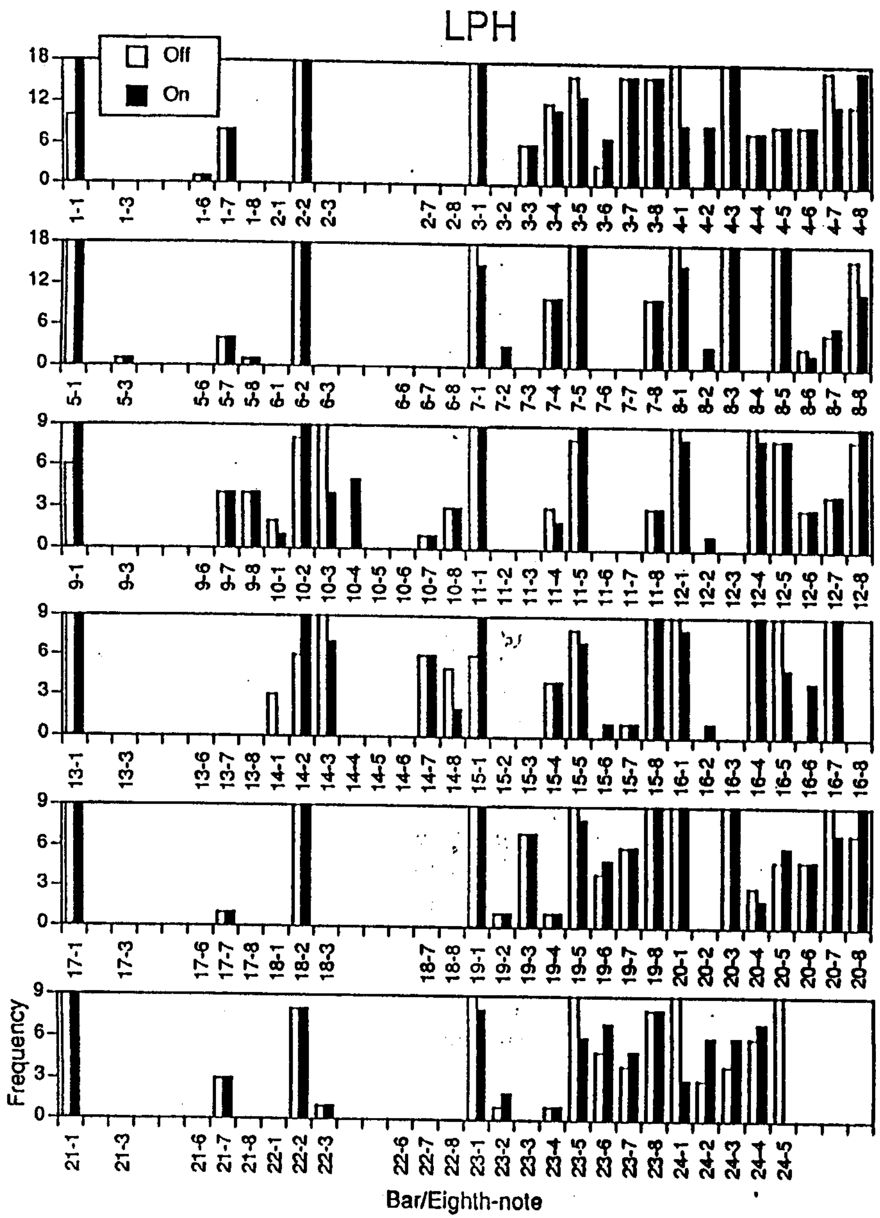

FIG. 3

Pedal use frequencies for pianist LPH. The layout of the figure corresponds to that of Figure 1, with the initial upbeat omitted. Each bar represents the frequency of pedal events within a particular IOI, added up over the nine performances and, in the case of bars 1-8, over the two renditions within each performance.

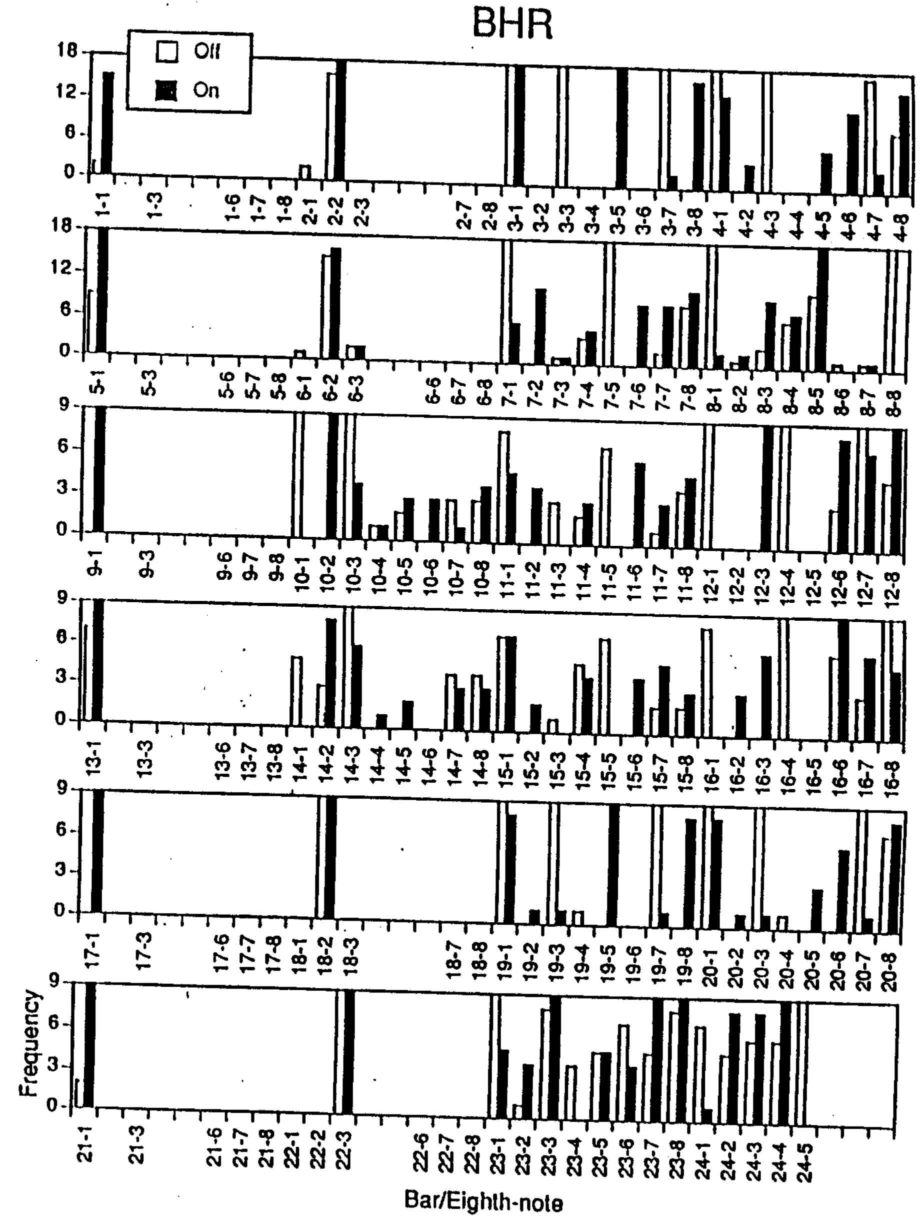

FIG. 4

Pedal use frequencies for pianist BHR.

the pedal was always down when a key was struck, whereas BHR showed some gaps in pedal use (see, *e.g.*, the intervals 3-3 to 3-5 or 12-1 to 12-3) and also had a tendency to lift the pedal just before the next key depression, so that pedal changes

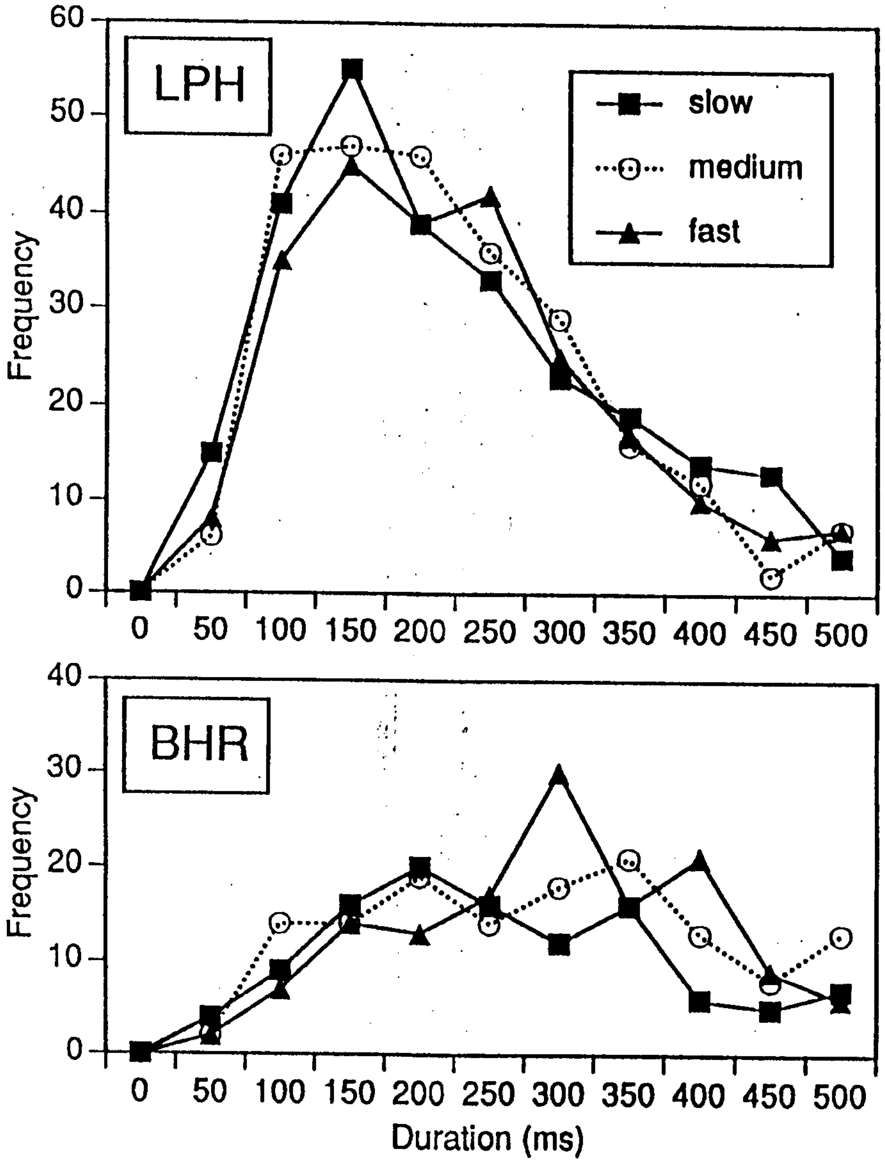

FIG. 5

Line histograms of pedal change times shorter than 500 ms in each pianist's performances at each of three tempi. Each data point represents a frequency count within a 50 ms bin whose *upper* bound is shown on the abscissa.

sometimes straddled tone onsets. This may be a reflection of poor pedalling technique. Finally, it is evident that the pedalling patterns are relatively simple and sparse during the first half of each 4-bar phrase, but considerably more complex during the second half, which corresponds to changes in the melodic and harmonic complexity of the music (*cf.* Fig. 2).

Pedal timing

Pedal change time distributions. Unlike pedal release times (PRTs) and pedal depression times (PDTs), whose determination was laborious, pedal change times (PCTs) could easily be obtained from the raw data by looking at pedal events only. Therefore, an initial rough analysis examined the distributions of PCTs across all performances within each tempo category. If pedal change is a stereotypical, reflex-like action pattern, the distribution of PCTs should exhibit a pronounced peak at some short duration, corresponding to the time needed to move the foot up and down. If there is absolute invariance, this peak should be independent of tempo. If the peak shifted with tempo, relational invariance would be indicated. This analysis included all PCTs, not just the ones in the six analysis sets.

The PCTs across the three performances within each tempo category were sorted into 50-ms bins for each pianist. Since only short times were of interest, an upper limit of 500 ms was adopted. The resulting distributions are shown as line histograms in Figure 5. It can be seen that neither pianist exhibited a narrow peak. PCTs were broadly distributed between 50 and 400 ms. LPH did show a peak around 100-150 ms, but it was not narrow enough to suggest a fixed action pattern. BHR, who yielded fewer short PCTs, did not show any clear peak at all. Neither pianist's distributions suggest any shift with tempo. This leaves open the possibility that PCTs, although they are obviously not absolutely invariant with respect to local tempo, are absolutely invariant with respect to global tempo. The following analyses examined this possibility and others at six structurally similar points in the score, which are aligned vertically in Figures 2–4. Because of the complexity of these analyses, however, only two of them will be presented in graphic detail.

Bar 2-2 and corresponding positions. This is the IOI that precedes the apex of each phrase. As the last IOI preceding a half-phrase boundary, it exhibits considerable expressive lengthening. It is special in two additional ways: It is the only eighth-note IOI bracketed (in the soprano voice) by tones of the same pitch, and it is the only IOI that contains two additional tone onsets within itself: In five of its eight occurrences (bars 2-2, 6-2, 2-2R, 6-2R, 18-2), two grace notes (part of an arpeggiated chord in the left hand) occur during the IOI; these notes are identical in bars 2-2(R) and 18-2 but different in bar 6-2(R). There are also explicit pedal instructions in the score at these points. The grace notes are absent in bars 10-2 and 14-2, where the beginning of an imitative melodic motive appears in the tenor voice (left hand). Bar 22-2 also lacks the grace notes, and the chord is not arpeggiated, though LPH chose to play it in this fashion, which elongated the IOI (measured to the onset of the last and highest tone of the chord) enormously. For this reason, and also because BHR did not pedal at all during this IOI, bar 22-2 was excluded.

Figure 6 shows the timing data. Time runs from bottom to top here. The beginning of the IOI (the onset of the first tone) is on the abscissa, whereas its end (the onset of the second tone) is signified by a filled square. Each data point represents an average across the three performances at each tempo. Each compartment of the figure shows the data for the three global tempi, for one particular position in the music. Thus, effects of global tempo can be seen within compartments, effects of local tempo (position) across compartments.

IOI duration obviously decreased as global tempo increased. IOI duration also varied across the five IOIs containing grace notes, being generally longer in bar

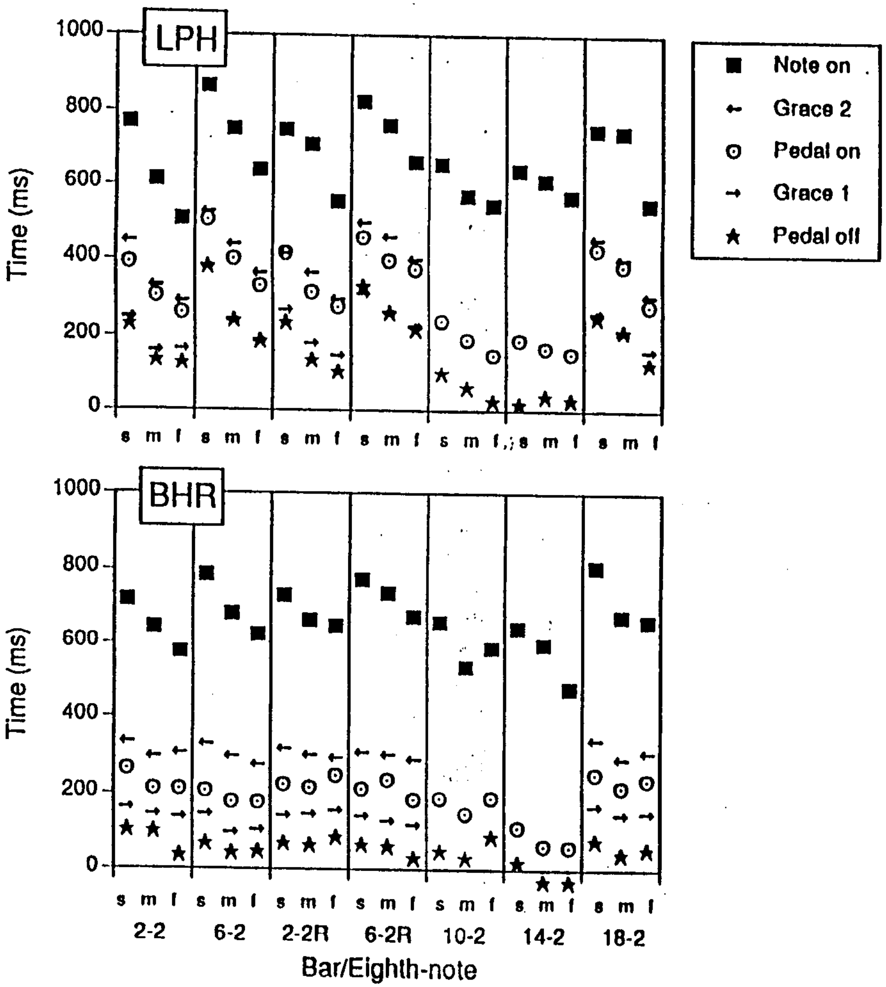

FIG. 6

Pedal timing data for bar 2-2 and corresponding positions. Each data point represents the average of measurements from three performances at each of three tempi: slow (s), medium (m) and fast (f). "Grace 1" and "Grace 2" represent grace note onsets. "Pedal off" marks pedal release time (PRT), "pedal on" marks pedal depression time (PDT), the interval between them is pedal change time (PCT), and "note on" marks the IOI duration.

6-2(R) than in bar 2-2(R), and longer in the repeats than in the first rendition of these bars (bar 18-2 being effectively a second repeat of bar 2-2). These differences represent variations in local tempo across structurally identical or highly similar positions in the music.

Both pedal releases and depressions occurred earlier in the two IOIs without grace notes, bars 10-2 and 14-2, than in the other bars, and somewhat earlier for BHR than for LPH. LPH's data for the "graceless" bars were not very informative, as not a single tempo or position effect reached statistical significance, for either absolute or relative measures of pedal timing. BHR, too, did not show any significant effects involving global tempo in those positions. However, his PRTs and PDTs occurred significantly earlier in bar 14-2 than in bar 10-2, both in absolute and in relative time, which contradicts any form of local invariance. Absolute or relative PCTs did not vary between those two positions.

Figure 6 suggests that, in the IOIs containing grace notes, pedalling times and grace note onset times were coordinated. Consider first LPH's data. Her pedal releases immediately preceded, or coincided with, the onset of the first grace note, and pedal depressions immediately preceded the onset of the second grace note. All these times clearly varied with global tempo, and they also varied across positions in the music, occurring later in bar 6-2(R) than in bar 2-2(R). The tempo and position main effects were significant for all absolute measures, except for PCTs, which did not show a tempo effect. The time between grace note onsets, however, even though it seemed very similar to PCTs, did decrease somewhat with increasing tempo. By contrast, tempo effects were absent for most relative time measures, except for PRT% and PCT%. These data, then, provide evidence for relational invariance of grace note onset times (*cf.* Repp, 1994a), as well as of PDTs; paradoxically, however, they suggest absolute invariance of PCTs, even though these intervals seemed to be very similar to the intervals between grace note onsets. Differences across positions were also obtained for most relative time measures, except for PDT% and the interval between grace note onsets. PCT% showed a very strong position effect, being relatively shorter in bar 6-2(R) than in bars 2-2(R) and 18-2, whereas the interval between grace note onsets was relationally invariant across positions. Thus, pedalling times and grace note onsets did not behave quite in the same way, contrary to what one might conclude from a superficial inspection of the data.

BHR's results were quite different from LPH's, even though his pedalling times and grace note onsets also seemed co-ordinated. Here, however, they alternated rather than nearly coincided. Tempo effects were virtually absent here, both for absolute and for relative measures. Significant tempo effects were observed only for the absolute and relative onset of the second grace note, which varied slightly with tempo but not enough to be relationally invariant. Most timing measures varied significantly across positions, however, and these differences tended to be larger for relative than for absolute measures. In contrast to LPH's data, most events occurred earlier in bar 6-2(R) than in bars 2-2(R) and 18-2, except for the absolute onset of the second grace note and both absolute and relative PCTs.

In summary, LPH's data suggest relational invariance of pedal depressions (along with grace note timing), but absolute invariance of PCTs. BHR's data are less clear but not inconsistent with a similar interpretation. Although pedal timing

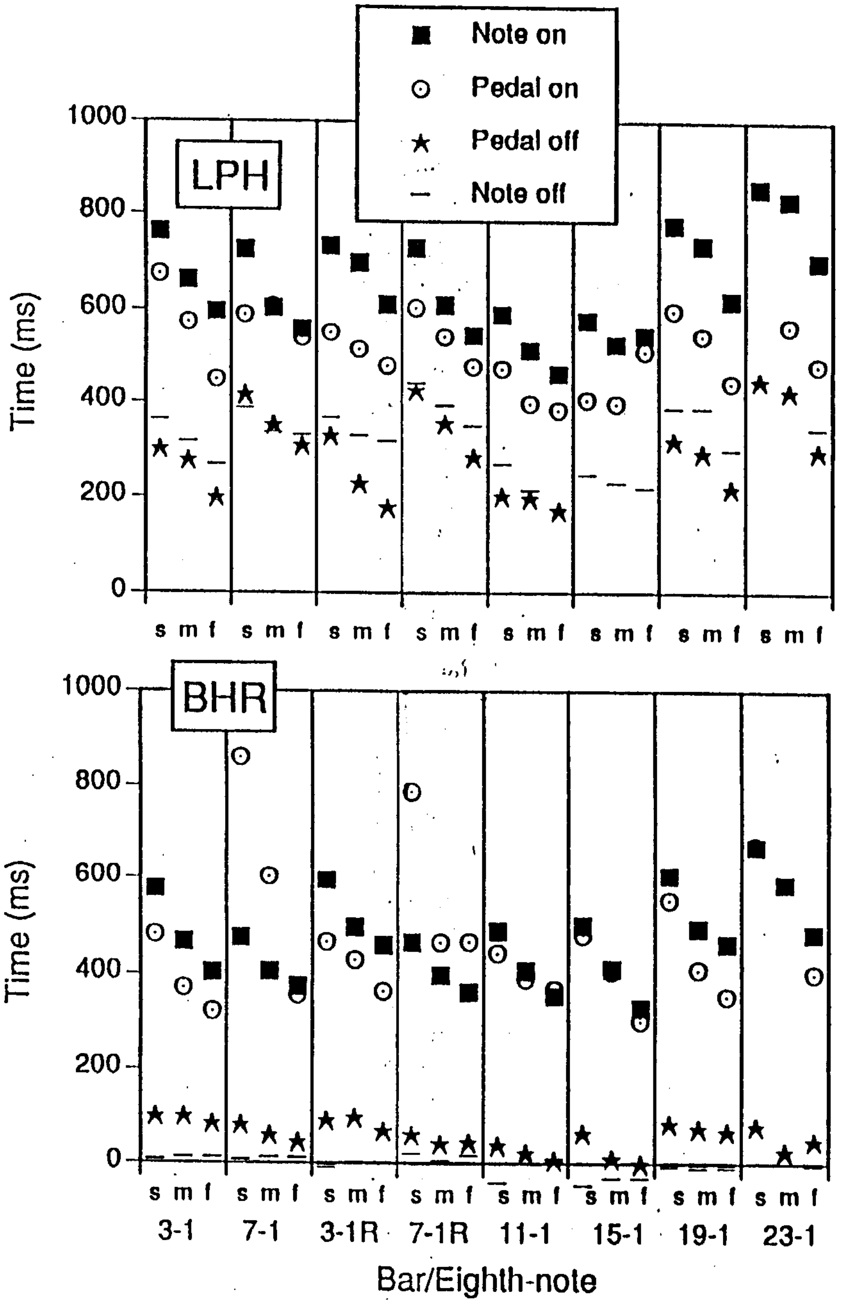

FIG. 7

Pedal timing data for bar 3-1 and corresponding positions. "Note off" marks key overlap time (KOT).

appears to be co-ordinated with grace note onsets, there is also evidence that it is not completely tied to those events. This was the only opportunity in these data to observe pedalling during relatively fast manual actions (grace notes) within an eighth-note IOI.*

Bar 3-1 and corresponding positions. The next vertical slice through the music was taken at bar 3-1 and the corresponding locations in bars 7-1, 3-1R, 7-1R, 11-1, 15-1, 19-1, and 23-1. In each case, the IOI starts with a chord, which accompanies the melodic line in the soprano voice; the end of the IOI is marked by the next, unaccompanied tone in the soprano voice (Fig. 2). Figure 7 shows the quantitative results, which also include the key release ("note off") times of the preceding tone in the soprano voice that defines the key overlap time (KOT).

Consider first LPH. Naturally, her IOI durations varied with tempo, but they also varied across positions: The IOI was shorter in the middle section (bars 11-1 and 15-1) and longer near the end of the piece (bar 23-1). Key releases of preceding tones occurred extremely late, reflecting a *legatissimo* playing style. KOTs varied significantly with tempo and especially across positions. PRTs, too, varied with tempo and across positions, and they usually fell in the vicinity of the key release times for the preceding tone. (PRTs were highly variable in bar 15-1, so these data are not shown in the figure and were not included in the statistical analysis.) While LPH's PRTs clearly were not absolutely invariant, they also did not exhibit relative invariance: In relative terms, too, the pedal release occurred earlier at the fast than at the slow tempo. There was also variation in PRT% across positions. PDTs varied with tempo and position, and for these times there was also a tempo by position interaction, with tempo effects being much larger in some bars (3-1, 23-1) than in others (7-1, 15-1). PDT%, on the other hand, did not vary with tempo, although it differed across positions and showed a position by tempo interaction. PCTs did not show a tempo main effect, but they varied across positions and exhibited a tempo by position interaction: It can be seen in Figure 7 that they decreased with tempo in some bars (3-1, 19-1) but increased with tempo in others (1-1R, 7-1R). Similarly, PCT% did not vary with tempo but did vary across positions and showed a position by tempo interaction. In sum, then, these data are more complex than the simple hypotheses of absolute *versus* relative invariance would predict.

BHR's IOIs varied with tempo and across positions, being somewhat longer in bars 3-1, 3-1R, and 19-1 than in bars 7-1, 7-1R, 11-1, and 15-1, and longest in bar 23-1. His preceding tone key releases and pedal releases occurred much earlier than LPH's, around the onset of the IOI and shortly afterwards, respectively. KOTs did not vary with tempo but did differ across positions. PRTs varied significantly with tempo and across positions. PDTs were rather variable; they either immediately preceded the onset of the second tone or followed it, especially in bar 7-1(R). Therefore, the means shown in Figure 7 are not always representative, and the PDTs were not subjected to statistical analysis. However, it is clear from Figure 7 that they varied with tempo and that they were not relationally invariant,

*Key-release times of the preceding tone (the C5 in the soprano voice) were not included in this analysis. In part, they are reported in Repp (1994a: Fig. 6, tone pair 4-5). For BHR, they were near the beginning of the IOI, but LPH often held the key down much longer than the notation would suggest, even beyond the onset of the tone terminating the IOI (especially in bar 6-2(R)). In those instances of "finger pedalling", the key release times are clearly irrelevant to pedal timing within the IOI.

at least not in bars 7-1(R). It is equally evident that PDTs were not absolutely invariant. However, PRT% did not vary significantly with tempo, and PDT%, when the pedal depressions were very close to second tone onsets, did not either. Therefore, PCT% must also have been approximately invariant in those cases. BHR's data then lend some support to the relational invariance hypothesis, in as much as pedal events seemed to be partially co-ordinated with tone onsets.

Other analysis sets. The remaining four analysis sets, whose results are not presented here in detail, were bars 3-5, 3-8, 4-1, and 4-3, and their corresponding positions in the music. The data were less complete in these sets, due to the paucity or absence of pedal events in some positions. In the final analysis set, some completely uninformative positions were replaced with adjacent positions: For LPH, bars 12-3 and 16-3, which contained no pedal events at all (*cf.* Fig. 3), were replaced with bars 12-4 and 16-4, respectively, and bar 24-3 was omitted due to inconsistency of pedalling patterns; for BHR, bars 8-3(R) were replaced with bars 8-5(R) for a similar reason (*cf.* Fig. 4). For details, see Repp (1994c).

Summary of statistical analyses. Tables 2–4 summarise the significance levels of the F-tests in the 2-way ANOVAS. No adjustment was made for the number of tests conducted, since the pattern of the data seemed more important than the significance levels of particular effects. Table 2 shows the main effects of (global) tempo, Table 3 those of position (*i.e.*, local tempo), and Table 4 the interactions between these two factors. "No test" indicates missing or insufficient data.

The IOI columns in the tables indicate that IOI duration always varied with global tempo (Table 2), as it should, and also across positions (Table 3), which demonstrates that local tempo variation was present in the data, even across positions

TABLE 2

Summary of tempo main effects (*i.e.*, global tempo effects).

Anal. set	*IOI*	*Pedal release time*		*Pedal depression time*		*Pedal change time*	
LPH		*PRT*	*PRT%*	*PDT*	*PDT%*	*PCT*	*PCT%*
2-2 etc.	**	**	*	**			*
3-1 etc.	**	**	****	**			
3-5 etc.	*						
3-8 etc.	***	*		***	**		
4-1 etc.	**						
4-3 etc.	**	*		*			
BHR							
2-2 etc.	****						
3-1 etc.	***	*		no test	no test	no test	no test
3-5 etc.	****			*		no test	no test
3-8 etc.	****	no test	no test	no test	no test	no test	no test
4-1 etc.	**	*		**		**	
4-3 etc.	****						

*p < ·05, **p < ·01, ***p < ·001, ****p < ·0001.

TABLE 3

Summary of position main effects (*i.e.*, local tempo effects).

Anal. set	*IOI*	*Pedal release time*		*Pedal depression time*		*Pedal change time*	
LPH		*PRT*	*PRT%*	*PDT*	*PDT%*	*PCT*	*PCT%*
2-2 etc.	***	****	***	***		**	****
3-1 etc.	****	****	****	****	****	****	****
3-5 etc.	****	**	*	***		*	
3-8 etc.	****			**	***		
4-1 etc.	****	**	****	****	***	****	****
4-3 etc.	****	****	****	****	****	****	****
BHR							
2-2 etc.	****		**	**	***		
3-1 etc.	****	****		no test	no test	no test	no test
3-5 etc.	***	****	****	****	****	no test	no test
3-8 etc.	****	no test	no test	no test	no test	no test	no test
4-1 etc.	****	****	****				
4-3 etc.	****	****	****	****	****		

*p < ·05, **p < ·01, ***p < ·001, ****p < ·0001.

TABLE 4

Summary of tempo by position interactions.

Anal. set	*IOI*	*Pedal release time*		*Pedal depression time*		*Pedal change time*	
LPH		*PRT*	*PRT%*	*PDT*	*PDT%*	*PCT*	*PCT%*
2-2 etc.							
3-1 etc.					**	**	*
3-5 etc.							
3-8 etc.							
4-1 etc.				**	*	**	**
4-3 etc.				*			
BHR							
2-2 etc.	*		*				
3-1 etc.				no test	no test	no test	no test
3-5 etc.						no test	no test
3-8 etc.		no test	no test	no test	no test	no test	no test
4-1 etc.		*	*				
4-3 etc.							

*p < ·05, **p < ·01, ***p < ·001, ****p < ·0001.

that were structurally as similar as possible. Table 4 shows that tempo by position interactions were generally absent, which indicates that IOI duration was very nearly relationally invariant in these performances (*cf.* Repp, 1994a).

For the pedalling times, Table 2 shows ten instances in which global tempo affected absolute but not relative times, as predicted by the relative invariance hypothesis, but only one instance where the opposite was the case, as predicted by the absolute invariance hypothesis. In three instances, both measures were affected by global tempo, and in the many remaining instances neither showed an effect. The results for PCT are particularly inconclusive. The absolute invariance hypothesis thus can be rejected for both PRT and PDT; relational invariance seems to hold occasionally for these events, but not always.

Table 3 shows that both absolute and relative pedalling times were strongly affected by local tempo in many instances. Thus, both the absolute and relative invariance hypotheses must be rejected with regard to local tempo. The high significance levels of many effects indicate that pedal timing exhibited reliable changes as a function of local tempo variation, but their pattern was more complex than predicted by any simple invariance hypothesis. Table 4 shows that, furthermore, global and local tempo effects sometimes interacted in a reliable fashion, which provides further evidence for the controlled complexity of pedal timing.

General Discussion

The present results demonstrate that pedal timing in expressive piano performance does not follow any simple pattern. Yet, the timing pattern is reproducible by the same pianist. Although there is variation in pedal use from one performance to the next, as already noted by Heinlein (1929b) and Banowetz (1985), whenever the pedal *is* used in the same position in the music, its action tends to be timed similarly. Although no direct measures of timing variability across performances of the same nominal tempo were calculated here, the pianists' relative consistency is reflected in the high significance levels of many of the statistical effects (Tables 2–4), all of which relied on a comparison (F ratio) of some main effect or interaction with its variability across performances within the same global tempo category. A more direct impression of the pianists' consistency may be gained by visually comparing the data in the first, third, and seventh compartments, as well as those in the second and fourth compartments, of Figures 6 and 7. They represent replications of the identical musical material *within* performances, and they generally show a very similar pedal timing pattern. (Note that some of the temporal variability in the raw data has been eliminated in these graphs by averaging over the three performances at each global tempo.)

Since nothing was known about precise pedal timing before this study began, the author may be forgiven for entertaining some perhaps simple-minded but heuristically useful hypotheses, for example that pedal release and depression times might be absolutely invariant. These hypotheses can now be safely rejected. Clearly, neither pedal releases nor pedal depressions occur at a fixed time after each key depression. This was especially clear in their variation across positions within (and between!) analysis sets. Only BHR's pedal releases showed some degree of invariance in that they usually occurred within 100 ms after a key depression, but their timing, too, varied significantly across positions. Absolute invariance did not hold across variations in global tempo either, although in some analysis sets there was not sufficient statistical evidence to reject this hypothesis. Even BHR's very early pedal releases, which could not be expected to vary much with global tempo, showed significant tempo effects in two analysis sets.

Perhaps the most promising hypothesis was that of absolute invariance of pedal change times. The rapid sequence of pedal release and depression is a highly overlearned and automatic action pattern, and one might think that it would be executed as quickly as possible without much regard to context or tempo. This proved to be wrong also. Both pianists showed a wide range of pedal change times, which varied especially across positions (compare also Figs. 6 and 7). The behaviour of pedal change times in the face of global tempo changes was less clear.

If absolute invariance does not hold, then the hypothesis of relational invariance seems the next most plausible candidate. However, it too finds little support in the present data. The variation across positions (local tempo) provides the most striking counter-evidence: All relative pedal timing measures exhibited large position effects, except for BHR's relative pedal change times. It is clear, however, from comparisons across analysis sets that these latter times were not constant either. Only with regard to variations in global tempo does the relational invariance hypothesis find some support: In a number of instances, relative pedal release and depression times did not vary with tempo, though their absolute timing did. However, there are also several counter-examples.

The present study did not attempt to explain the patterns of pedal timing with reference to the structural features of the music that govern expressive manual timing. However, some attention was paid to the timing of the key release for the preceding melody note which, in LPH's case at least, seemed to depend in part on the harmonic relationship of the overlapping tones. Delayed key releases seemed to go with delayed pedal releases and depressions, at least across analysis sets. Within analysis sets, however, there seemed to be no precise coordination of key and pedal releases, even though they tended to occur at roughly the same time in LPH's playing (*cf.* Fig. 7).

A tendency of pedalling events to align themselves with manual events was observed in several instances. In the first analysis set (bar 2-2, etc.), pedal actions nearly coincided with grace note onsets for LPH, and they alternated with grace note onsets for BHR, as if these actions were "in phase" in one case and "out of phase" in the other. This is reminiscent of the preferred phase relationships found in studies of bi-manual co-ordination in simple repetitive movements (*e.g.*, Haken, Kelso and Bunz, 1985), but the present situation is different in many ways: The moving body parts are of different sizes (fingers *versus* foot), the timing is relatively rapid, and neither movement is oscillatory in character (although a pedal change may be considered a single cycle of a potentially continuous manoeuvre). In several other instances there was a tendency for pedal depressions to coincide with note onsets, and BHR's early pedal releases may be considered aligned with note onsets as well. However, there were also many instances of non-alignment, and the data are basically inconclusive as to whether there were any preferred phase relationships between manual and pedal actions.

There were many differences in pedal use and timing between the two pianists, LPH and BHR. While LPH had undergone professional training as a concert pianist and therefore must have given considerable conscious attention to her pedalling technique at various times in her career, BHR is an amateur who never has given much thought to his pedalling skills. Yet, the various individual differences cannot immediately be attributed to differences in skill level, as individual differences in pedal timing may well exist between pianists on the same level of expertise. That is another issue worthy of further research. One skill-related difference between LPH and BHR, however, was in their key overlap times (see also Repp, 1994a): LPH generally played in a *legatissimo* style, which almost certainly enhanced the beauty of her performances, and which was not within BHR's capabilities. In fact, BHR sometimes exhibited gaps between notes that could have been played *legato*. This difference in manual playing style was the likely cause of the most obvious difference between the two pianists in pedal timing, *viz.*, in the early (BHR) *versus* late (LPH) occurrence of pedal releases within an IOI.

In summary, the present investigation initiated the study of a little investigated topic, pedal timing, in the most complex, but ecologically most valid, situation imaginable: artistic music performance. The results present a rather complex picture of pianists' pedalling skill whose clarification will require considerable further research. Experiments employing simpler materials in more artificial situations may help unravel the factors that influence pedal timing, but a glimpse of the richness of real-life data is a good antidote to future over-simplification.

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