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The effect of tempo on pedal timing in piano performance

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Abstract The temporal coordination of hand and foot actions in piano performance is an interesting instance of highly practiced, perceptually guided complex motor behavior. To gain some insight into the nature of this coordination, ten pianists were asked to play two excerpts from the piano literature that required repeated use of the damper pedal to connect successive chords. Each excerpt was played at three prescribed tempos on a Yamaha Disklavier and was recorded in MIDI format. The question of interest was whether and how changes in tempo would affect the timing of pedal releases and depressions within the periods defined by successive manual chord onsets. Theoretical possibilities ranged from absolute invariance (variable phase relationships) to relative invariance of pedal timing (constant phase relationships). The results show that, typically, the timing of pedal actions is neither absolutely nor relatively invariant: As the tempo increases, both pedal releases and depressions usually occur a little sooner and pedal changes (release-depression sequences) are executed a little more quickly, but these effects are proportionally smaller than the changes in manual (and pedal) period duration. Since this may be due to unequal changes in peripheral hand and foot kinematics with tempo, it remains possible that there is invariance of either kind at the level of central motor commands. However, it is the peripheral timing that produces the acoustic consequences musicians try to achieve.

Introduction

Pedaling is an important component of piano performance that has only rarely been studied with scientific rigor. It has qualitative and quantitative aspects: pedal use and pedal timing, respectively (Repp, 1996). *Pedal use* refers to the purpose, frequency, place in the score, and general manner of pedaling. This topic is primarily of pedagogical and musicological interest, though individual differences and consistency in pedal use may also be examined from a psychological perspective (Heinlein, 1930). *Pedal timing* refers to the precise timing of the foot actions relative to the manual actions on the keyboard and relative to each other. This aspect is primarily of psychological interest, as it bears on theories of motor control and coordination as well as on the psycho-acoustics of piano sound.

The present study is concerned with the damper pedal only, and with the most common form of its use, called syncopated or *legato* pedaling (Banowetz, 1985), which serves to connect successive tones or chords that are difficult or impossible to connect with the fingers alone. To prolong the first of a series of successive chords, the pedal is depressed while the fingers still hold down the keys. When the fingers leave the keys to reach for the second chord, the first chord is sustained because the pedal prevents the dampers from falling onto the strings. As soon as the second chord is struck, the pedal is released so as not to cause extensive overlap of the two sonorities, especially when they are dissonant with each other. The dampers extinguish the vibrations in all strings whose keys are not currently depressed. Then the pedal is depressed again to prolong the second chord, and so on.

The timing of pedal actions can be measured relative to keyboard actions and relative to other pedal actions registered via a MIDI system, as is illustrated in Fig. 1. Two successive key depressions (MIDI "note on" events) define a manual *interonset interval* (IOI). The interval between key depression and key release (MIDI "note off") is the *key dwell time*, or MIDI note duration (MND in Fig. 1). The acoustic *tone duration* lasts from the key depression to some time beyond the next pedal release, due to a substantial post-release

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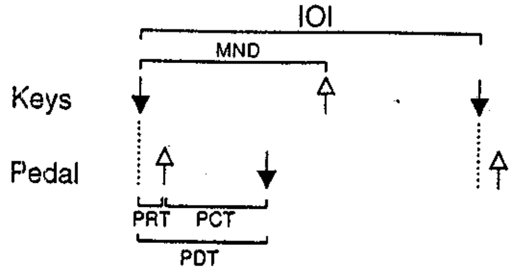


Fig. 1 The temporal relations between keyboard and pedal events. Time runs from left to right. *IOI* = interonset interval; *MND* = *MIDI* note duration (key dwell time); *PRT* = pedal release time; *PDT* = pedal depression time; *PCT* = pedal change time

decay time (Repp, 1995, 1997). Following terminology introduced by Repp (1996), *pedal release time* (PRT) is defined as the interval between a key depression and a pedal release in its vicinity; it is positive when the pedal release follows the key depression and negative when it precedes it (as it may occasionally). The interval between a pedal release and an immediately following pedal depression (i.e., within the same IOI) is the *pedal change time* (PCT). Finally, the interval from a key depression to a pedal depression is the *pedal depression time* (PDT);[1] as can be seen in Fig. 1, PDT = PRT + PCT. The key depressions, pedal releases, and pedal depressions in an extended passage of syncopated pedaling may be regarded as three staggered quasi-periodic activities, with PRT/IOI, PDT/IOI, and PCT/IOI being measures of their momentary phase relationships.

Pedaling is a highly automatized activity that usually is not given much thought during performance. Pedal changes occur so frequently that the rapid up-down movement of the foot may well constitute a single integrated action pattern. However, the pedaling needs to be coordinated with, and hence is constrained by, the manual actions on the keyboard. Pedal releases are closely tied to key depressions. They are responsible for creating the impression of legato or connectedness between successive tones or chords, and they must be neither too early nor too late with respect to the key depressions, or else either gaps or annoying overlaps will be heard. Pedal depressions must occur before key releases, or else the tones will not be properly prolonged. This requirement places an upper limit on the pedal change time (PCT). A lower limit on PCT is set by the maximum speed of the up-down foot movement; the limit can be reduced further by depressing the pedal only partially. All these relationships and constraints are subject to the pianist's continuous auditory monitoring of the resulting sound patterns.

Arguably, this form of perceptually guided interlimb coordination is a good deal more complex than any motor tasks that have been investigated in the laboratory. Studies of interlimb coordination have typically employed the bimanual execution of polyrhythmic taps (e.g., Summers, Todd, & Kim, 1993) or of other kinds of differentially parameterized movements within a common time frame (e.g., Kelso, Southard, & Goodman, 1979; Swinnen, Walter, Lee, & Serrien, 1993; Heuer, Schmidt, & Ghodsian, 1995). These tasks are usually difficult to execute, and the researchers' focus is on coordinative strategies that facilitate performance. While subjects may be given considerable practice with a task, it is hardly comparable to the thousands of hours pianists have spent at the keyboard. Coordinative strategies that may be adopted spontaneously, due to inherent preferences of the motor system, may be abandoned with extensive practice when task requirements favor alternative strategies (Swinnen et al., 1993). There can be little doubt that experienced pianists' pedaling has become entirely subservient to the goal of achieving intended sound patterns, whether or not the required coordination matches the inherent dynamics of their motor systems. However, the activity of the foot is not entirely constrained by that of the hands, and theoretical concepts developed in other coordinative task environments can be applied to piano performance as well.

One question that may be asked about pianists' hand-foot coordination is whether the two activities are governed by a single integrated motor program or by separate, linked routines (cf. Heuer et al., 1995). Heinlein's (1930) finding that pianists could pedal properly only when they actually played the music but not when the music was reproduced on a player piano suggests a high degree of integration of manual and pedal actions, though the performance measure was frequency of pedal use rather than timing. The present study examines the effect of changes in global tempo on pedal timing. If the tempo of a performance is changed, so that its manual IOIs are lengthened or shortened more or less uniformly (Repp, 1994), how does the pedal timing change within the IOIs? Two simple hypotheses may be derived from the motor control literature (e.g., Gentner, 1987; Heuer, 1991; Viviani & Laissard, 1991). The *absolute invariance* hypothesis predicts that the pedal timing intervals (PRT, PCT, and PDT) remain constant as IOI increases. This means that the phase relationship between manual and pedal activities is not constant but changes with tempo. By contrast, the *relative invariance* hypothesis predicts that all pedal timing intervals stretch and shrink proportionally with the IOIs, so that constant phase relationships are maintained. Support for this second hypothesis would indicate that hand and foot actions are governed by a single

[1] *PDT* designates the time at which the pedal is depressed within an IOI, not the total time during which the pedal is held down, which is the *pedal dwell time* and equals $IOI_i - PDT_i + PRT_{i+1}$.

central motor program with a multiplicative rate parameter (Schmidt, 1985), whereas support for the first hypothesis would suggest that foot actions are controlled independently, even though they are evidently anchored to manual actions (key depressions). Intermediate results are possible.

It should be noted that, even if the measured pedal timing intervals do not scale proportionally with tempo, it is nevertheless possible that relative invariance holds at the level of a central motor program. Likewise, it is possible for absolute invariance to hold centrally even if the measured intervals are not absolutely invariant. This is so because the measured intervals are based on landmarks in peripheral kinematics that may occur at variable delays after central motor commands are issued (Wing & Kristofferson, 1973; Heuer, 1988, 1991). A formal model for dealing with this complicating factor in the context of interlimb coordination has been developed recently (Heuer et al., 1995), but it cannot be easily applied to piano pedaling. The present study concerns peripheral timing only, though the problem of central timing will be considered again in the Discussion section.

In a previous investigation, the author measured the pedal timing in two pianists' performances of Robert Schumann's "Träumerei" at three tempos (Repp, 1996). The results did not yield clear support for either invariance hypothesis. Although one or the other kind of invariance seemed to hold locally, a variety of patterns was observed. Pedal timing seemed to be affected by changes in tempo, but not in a relationally invariant fashion. The generality of this finding is uncertain, however. The music was complex, and the possibility of finger legato throughout may have made pedaling more of a coloristic device than a means of achieving connectedness. One of the two pianists exhibited an unusual degree of finger legato (i.e., large overlaps of successive key depressions), whereas the other one did not. Correspondingly, there were large individual differences in pedal timing, as the pedal was usually released after the keys. Large expressive timing variations (i.e., systematic within-tempo variations of IOI duration, or variations in local tempo) within each performance further complicated the situation, as they, too, affected pedal timing.

There is reason to expect the time of pedal release (PRT) to vary with tempo. Repp (1995, 1997) has shown that pianists' finger legato decreases as tempo increases (i.e., as IOI duration decreases), and since legato pedaling has the same connecting function as finger legato, it may well show a parallel tendency. The progressive decay of sustained piano tones implies that long tones have a shorter post-release (damped) decay time than short tones, so that a greater degree of key/pedal depression overlap can be perceptually tolerated between long tones or chords than between short ones. However, it is also possible that the observed effect of tempo on finger legato was due to purely motoric constraints on finger kinematics at rapid tempos, and such constraints would not apply to the temporal relations between hand and foot. Thus, absolute invariance of PRT remains a reasonable theoretical possibility.

At first glance, it is not clear why pedal change time (PCT) should vary with tempo at all. There is nothing to be gained from lengthening PCT as tempo decreases. If tempo increases, however, the key dwell time may be reduced and may approach the pedal depression time (PDT). In that case, a shortening of PDT and of PCT may be the result because the pedal depression should precede the key release. It is possible, of course, for PRT and PDT to covary, so that PCT remains constant. Indeed, Repp (1996) found that PCT was nearly invariant with changes in global tempo; however, it varied greatly as a function of variations in local tempo (i.e., expressive timing). This latter finding casts doubt on the assumption that pedal change is a fixed action pattern.

The present study reinvestigated the effect of global tempo on pedal timing, using more homogeneous musical materials that did not allow much finger legato and did not encourage large expressive timing variations. Because pedaling was necessary to achieve legato articulation in these passages, key dwell time (early key release) was given a better chance to exert a constraint on pedal timing than in the previous study. A larger number of pianists was recorded in the hope that a clearer picture would emerge with regard to the two invariance hypotheses.

Method

The participants were ten pianists whose technical skills ranged from professional to advanced amateur level. Two were third-year (artist's diploma) graduate students of piano at the Yale School of Music, one was a first-year graduate student, one was a second-year certificate (undergraduate) student, and five were undergraduates in Yale College, all active pianists since childhood who were paid for their services. The author, a serious amateur, also participated. The pianists played two excerpts from the standard piano literature, shown in Fig. 2. In the Beethoven except, a chorale-like melody is spelled out in right-hand chords while left-hand octaves serve as accompaniment: then the melody is repeated in left-hand octaves, with right-hand filler notes. The Brahms excerpt starts out similarly but is more massive and chordal throughout, it builds from a hushed beginning to a *fortissimo* climax. Both excerpts are in 6/8 meter, though this was not indicated in the photocopies presented to the pianists (Fig. 2).[2]

The performances were played on a Yamaha Mark II Disklavier grand piano whose mechanical actions were registered by built-in sensors and were recorded in MIDI format by a Macintosh computer. The pianists were given a few minutes to familiarize themselves with the Beethoven excerpt and then were asked to play

[2]It was thought that the meter would be obvious from the dotted quarter notes (however, see Footnote 4 below) and that most pianists would recognize the excerpts as familiar. The first bar of the Beethoven excerpt was also lacking a bass clef.

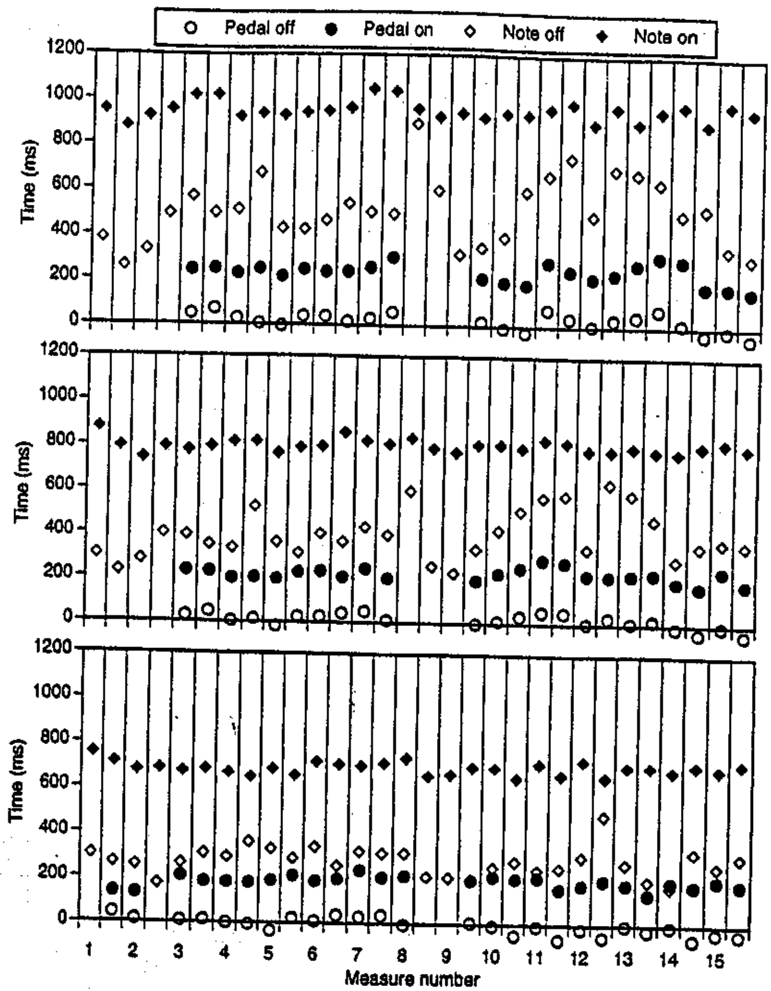
Fig. 2 The musical excerpts: measures 103–118 from the fourth movement of Beethoven's Sonata in C major, Op. 2, No. 3 (Peters Edition), and measures 140–164 from the fifth movement of Brahms's Sonata in F minor, Op. 5 (Schirmer edition). They are shown in the form in which they were presented to the pianists, except that the measures have been renumbered

it once at each of three tempos indicated by a metronome. Then the procedure was repeated with the technically more demanding Brahms excerpt. The prescribed tempos were 60, 72, and 84 beats (dotted quarter notes) per minute, in that order, for both pieces. The fastest tempo corresponded approximately to the tempo that is normally taken in this music. The metronome was flashing silently, and the pianists were asked not to look at it while playing. The instructions stressed that fluency was more important than accuracy. Naturally, the performances were not of recital quality (there were some wrong and missed notes), but most seemed adequate for the purpose. The Beethoven data of two undergraduate pianists were rejected because of erratic pedaling, and the Beethoven data of a third pianist were lost due to human error, which left data from seven pianists for this excerpt. The Brahms performances of one undergraduate pianist were rejected because of hesitations, leaving nine pianists' data for that excerpt.

The MIDI files were imported as text into a spreadsheet program, and the onset of the highest note in each chord that coincided with a beat was labeled, except during the second half of the Beethoven excerpt, where the lower notes of the left-hand octaves served as the reference. Then the IOIs between labeled note onsets were calculated, and the three pedal timing intervals (PRT, PCT, PDT) were computed with reference to the labeled note onsets. Finally, the earliest note offset was determined in each chord and yielded the (shortest) MIDI note duration (MND).[3]

[3]It was assumed that the pedal depression time would be constrained by the earliest note offset rather than by the offset of the labeled melody note, which tended to occur later, often (when this was possible) close to the onset of the following chord. The MND thus was not usually the dwell time of a specific key, but rather the interval between the melodically most important note onset and the (for pedaling) most important note offset.

Fig. 3 Results of one pianist (D.G.) for the Beethoven excerpt. The three panels represent slow, medium, and fast tempo, respectively. Pedal events are shown only for measures with regular legato pedaling. The four MIDI terms in the legend are equivalent to PRT, PDT, MND, and IOI, respectively



Results

To illustrate the general nature of the data, Fig. 3 shows the results of one of the two advanced graduate student pianists (D.G.) for the Beethoven excerpt. The three panels represent slow, medium, and fast tempo, respectively. Each vertical compartment represents one beat, within which four measured time points are plotted: "pedal off" (= PRT), "pedal on" (= PDT), "(earliest) note off" (= MND), and "(next) note on" (= IOI). The zero line represents the "note on" initiating the IOI. Missing pedal events mean either that there was no pedaling in that IOI or that it did not conform to typical legato pedaling.

It can be seen that D.G. kept IOI durations (filled diamonds) fairly steady and just slightly under the beat durations suggested by the metronome (1000, 833, and 714 ms, respectively).[4] Thus, as expected, variations in local tempo (expressive timing) were relatively small. D.G.'s early note offsets (open diamonds) were much more variable (they presumably reflect fingering and the physical distance between successive chords) but clearly got shorter and decreased in variability as the tempo increased. D.G.'s pedal timing seemed fairly stable, especially his pedal change times (the distances between pedal off and pedal on). Both pedal release times (open circles) and pedal depression times (filled circles) seemed to decrease somewhat with IOI.

To assess these relationships more precisely, correlations and linear regressions were computed between IOI and other variables, combining the data from all three tempo conditions (for D.G., $n = 72$ for measures of pedal timing, $n = 90$ for early key releases). A significant correlation of IOI with any variable is evidence against absolute invariance of that interval, whereas a significant correlation of IOI with any variable expressed as a percentage of IOI is evidence against relative invariance of that interval. The contribution of variation in local tempo (i.e., variation of IOI within tempo conditions) to these correlations was considered negligible. For D.G., the shortest MIDI note duration (MND) clearly decreased with IOI ($r = 0.66$, $p < .001$), but the regression line had a negative intercept, which

[4] The pianists' accuracy in following the suggested tempos was not of great concern, as long as they changed their tempo significantly across the three conditions. However, it should be mentioned that one pianist in the Beethoven excerpt (P.W.) and one in the Brahms (K.S.) apparently interpreted the meter as 3/4 rather than 6/8; they played about 33% slower than the other pianists.

Table 1 Correlations of absolute (PRT, PDT, PCT) and relative (PDT—, PCT%) measures of pedal timing with IOI duration, average within-tempo correlations between PRT and PDT [r(R, D)] and between PRT and PCT [r(R, C)], and average durations of PRT and PCT (averaged across all three tempos) for the Beethoven and Brahms excerpts

(a) Beethoven excerpt

Pianist	PRT	PDT	PDT%	PCT	PCT%	r(R, D)	r(R, C)	average (ms) PRT	average (ms) PCT
P.L.	0.64***	0.58***	0.15	0.50***	− 0.14	0.70***	0.54**	4	216
D.G.	0.45***	0.58***	− 0.24	0.27*	− 0.58***	0.69***	− 0.31	9	204
T.C.	0.40**	0.40**	− 0.24	0.23	− 0.47***	0.65***	0.05	41	237
P.W.	0.13	0.30*	− 0.29*	0.26*	− 0.25*	0.18	− 0.26	61	341
M.C.	0.29*	0.55***	− 0.27*	0.49***	− 0.39**	0.52**	− 0.18	36	222
M.A.	0.29*	0.19	− 0.58***	0.01	− 0.34**	0.42*	− 0.14	43	324
B.R.	− 0.02	0.40**	− 0.28*	0.44***	− 0.24	0.43*	− 0.47*	15	272

(b) Brahms excerpt

Pianist	PRT	PDT	PDT%	PCT	PCT%	r(R, D)	r(R, C)	average (ms) PRT	average (ms) PCT
P.L.	0.48***	0.39**	− 0.07	0.26*	− 0.36**	0.77***	0.49*	0	154
D.G.	0.49***	0.63***	− 0.08	0.51***	− 0.38**	0.60**	− 0.05	21	173
T.C.	0.26*	0.77***	− 0.33**	0.70***	− 0.34**	0.53**	− 0.13	43	190
P.W.	0.01	− 0.15	− 0.38**	− 0.15	− 0.35**	0.26	− 0.36	38	170
K.S.	0.68***	0.80***	− 0.22	0.63***	− 0.27*	0.82***	0.23	182	155
M.C.	0.41***	0.63***	− 0.60***	0.58***	− 0.67***	0.73***	0.21	62	173
M.A.	0.20	0.19	− 0.40**	0.10	− 0.42***	0.36	− 0.17	50	246
P.C.	0.30*	0.61***	− 0.06	0.56***	− 0.13	0.43*	0.12	14	162
B.R.	0.07	0.77***	0.37**	0.72***	0.45***	0.12	− 0.26	31	157

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

means the change in MND was more than proportional to that in IOI. Consequently, MND% (= MND/IOI * 100) still correlated positively with IOI ($r = 0.37$, $p < .001$). Of the pedal timing measures, PRT decreased with IOI ($r = 0.45$, $p < .001$) as did PDT ($r = 0.58$, $p < .001$), but PCT decreased only slightly ($r = 0.27$, $p < .05$). PRT% still decreased with IOI ($r = 0.41$, $p < .001$), while PDT% increased slightly ($r = -0.24$, $p < .05$), and PCT% increased much more ($r = -0.58$, $p < .001$). These results suggests weak tendencies towards absolute invariance of PCT and towards relative invariance of PDT. PRT, of course, could not really show relative invariance because it varied around zero.

Although MNDs decreased with IOIs and thus could have constrained the timing of pedal depressions, it is clear from Fig. 3 that D.G.'s pedal depressions were not influenced at all by the highly variable timing of early key releases within tempo conditions. The figure also reveals a parallelism between PRT and PDT within each tempo condition. Their correlation is 0.84 ($p < .001$) at the slow tempo, 0.78 ($p < .001$) at the medium tempo, and 0.44 ($p < .05$) at the fast tempo, or an average correlation of 0.69 ($p < .001$). On the other hand, the average within-tempo correlation between PRT and PCT is nonsignificant ($r = -0.31$). This suggests a strong tendency towards absolute invariance of D.G.'s pedal change times within each tempo condition.

Similar analyses were conducted for the other six pianists, and the results are summarized in Table 1, which also includes the average durations of PRT and PCT for each pianist. The pianists are arranged roughly in order of decreasing experience, with the three graduate students on top, followed by the undergraduate pianists and the author.[5] The corresponding data for the Brahms excerpt are shown in the lower half of the table.

For most pianists, the time of pedal release (PRT) decreased with IOI. This represents a tendency to play less legato at faster tempos, which is in agreement with observations on finger legato (Repp, 1995, 1997). Two pianists, however (P.W. and B.R.), were unaffected by tempo and thus showed absolute invariance of PRT in both excerpts. As already pointed out, the question of relative invariance does not really arise when the PRTs are in the vicinity of zero; in most cases, the correlation between PRT% and IOI (not shown in Table 1) was similar to that between PRT and IOI. Average PRTs ranged from 0–62 ms, except for one pianist (K.S.) who had exceptionally long PRTs in the Brahms. (Her Beethoven data were lost.) She showed the highest correlation between PRT and IOI ($r = 0.68$, $p < .001$), but no correlation between PRT% and IOI ($r = -0.05$), indicating relative invariance. A second pianist with relatively long PRTs in the Brahms, M.C., showed similar results. Thus, all three possible patterns (absolute invariance, relative invariance, and neither) were represented for PRT.

[5] The author is difficult to classify relative to the student pianists. While he is technically less advanced and practices much less, he has played for many more years and is more familiar with the piano literature, such as the sonatas from which the excerpts were taken.

The time of pedal depression (PDT) showed an even stronger tendency to decrease with IOI. Again, however, there were two exceptions (P.W. and M.A.). Moreover, these pianists had significant negative correlations between PDT% and IOI in both excerpts, which indicates absolute invariance of PDT. Several other pianists (most notably P.L. and D.G.) showed just the opposite pattern, namely, relative invariance. Yet others (such as M.C.) showed results that were incompatible with either kind of invariance. Correlations between PDT% and IOI generally tended to be negative, indicating that PDT changed less than proportionally with IOI.

The interval of greatest interest was the pedal change time (PCT), because of the theoretical possibility that pedal change is an integrated unit of action with invariant timing. However, only one pianist (M.A.) showed absolute invariance of PCT in both excerpts; another (P.W.) did so in the Brahms only, and there are a few other, more marginal cases. For others, PCT decreased with IOI while PCT% did the opposite, which indicates that the change in PCT was less than proportional to IOI. A few cases suggest relative invariance but are not consistent between the two excerpts. B.R. was the only pianist to show a positive correlation of PCT% with IOI, in the Brahms excerpt.

Individual differences were also striking with regard to the within-tempo correlation between PRT and PDT [$r(R, D)$]. Five pianists (including D.G.; cf. Fig. 3) showed a strong coupling between pedal releases and depressions, and four of them showed no significant correlation between PRT and PCT, which is in agreement with absolute invariance of PCT within conditions. The exception was P.L., who showed a tendency for PCT to covary with PRT. The remaining pianists showed little or no relation between PRT and PDT, or between PRT and PCT.

Individual differences in the average durations of pedal release and pedal change times can be seen in the final two columns of Table 1. Four pianists (P.L., D.G., B.R., P.C.) had rather short PRTs; interestingly, the same pianists also had relatively short key depression overlaps in a study of finger legato (Repp, 1997). The exceptionally long PRTs of K.S. have already been pointed out; this pianist also had long overlaps in finger legato. Average PCTs were shorter in the Brahms than in the Beethoven.[6] This in itself argues against PCT as an invariant action pattern. Across pianists, average PCT tended to covary with average PRT, both in the Beethoven ($r = 0.73$, $p < .05$) and in the Brahms ($r = 0.55$, $p < .10$, with K.S. omitted because of her exceptionally long PRTs). In other words, pianists who played with greater pedal legato also tended to change pedal more slowly. Individual differences in average PRT showed some consistency across the two musical excerpts ($r = 0.71$, $p < .05$). The corresponding correlation for PCT was 0.46 (n.s.).

[6]Bars 17–20 in the Brahms excerpt contain hemiolas, which amounts to an accelerated tempo (see Fig. 2). Most pianists did not exhibit regular legato pedaling during those passages. Those who occasionally pedaled showed much shorter PCTs. However, even those pianists who did not provide any useful pedaling data in those bars (P.L., D.G., M.A.) showed shorter average PCTs in the Brahms than in the Beethoven.

Discussion

The results are essentially in agreement with those of Repp (1996) in that they suggest that, most often, pedal timing is neither absolutely nor relatively invariant across changes in global tempo. Although some individual pianists do exhibit absolute or relative invariance of one or another measure, it is not clear whether this is a stable aspect of personal pedaling style that has generality beyond the musical excerpts examined here. Another way of describing the main finding is that there is usually no constant phase relationship between the quasi-periodic activities of manual key depressions and either pedal depressions or pedal releases, nor is there typically a constant absolute delay of pedal actions relative to manual actions.

It must now be asked whether more straightforward temporal relations might exist at a central level of motor commands. Following Wing and Kristofferson (1973), Heuer (1988, 1991; Heuer et al., 1995) has argued that relational invariance may be maintained at a central level of motor programming even when it is violated in the timing of overt actions, as long as there is a linear relationship between the independent and dependent intervals of interest. The intercept of the regression line may be interpreted as the difference between peripheral motor delays for the events that delimit the dependent interval. This argument could be applied to the present data, which were generally compatible with the assumption of linearity. However, while it is possible in principle to attribute individual differences in correlations to individual differences in motor delays, it is not clear why motor delays should differ greatly from one individual to the next.

The linear function relating pedal change time to IOI generally had a positive intercept, which might mean that there is a longer motor delay for a pedal depression than for a pedal release. This proposition could be tested in simple reaction-time tasks. There is a more obvious explanation, however: A pedal change requires a certain minimum time to be executed, whether the limit is set by the maximum movement speed of the foot or by the upward travelling time and downward resistance of the pedal. Therefore, PCT cannot decrease indefinitely as tempo increases. Although PCTs can be shortened by not depressing the pedal fully, it appears from the limited data available (including Repp, 1996) that the lower limit is around 100 ms. Thus, the greater motor delay for pedal depressions than for pedal releases has mechanical rather than neural causes. For those pianists, then, whose PCT did covary with IOI, there may have been relative timing invariance at a central level.

There is an additional complicating factor, however: The kinematics of hand and especially foot actions may change with global tempo. That is, the velocity of pedal depressions and releases may increase with tempo, perhaps in different degrees, while the depth of pedal depressions may decrease. In other words, the various motor delays may change with tempo. If so, it is very difficult to tell from peripheral data what is going on at a central level. It would be necessary to conduct a detailed analysis of hand and foot kinematics during piano performance to obtain a better understanding of these relationships. However, while the modeling of central timing is of theoretical interest, it is the peripheral timing that is of practical significance in piano playing. It is the timing of the actual pedal releases and depressions that produces the acoustic consequences that the pianist intends to achieve and that he or she monitors continuously.

From this perspective, the timing of pedal releases is most significant, as it affects the degree of legato or connectedness between successive tones or chords. The decrease in PRT with IOI in a number of pianists is in agreement with an observed decrease in finger legato with IOI in the playing of simple tone sequences (Repp, 1995, 1997). The PRT durations, however, are a good deal shorter than the key overlap times in finger legato for the same pianists, even though the IOIs in the present excerpt were about twice as long. The difference may be due to the nature of the sequences: Acoustic overlap between successive chords may be less tolerable perceptually than between single tones. Alternatively, the difference may have a kinematic origin: Pedal releases may be tightly coupled with key depressions at a central level of motor commands, and the individual differences in peripheral PRTs may reflect differences in the velocity of the foot raising movement.

The involvement of the same pianists in both pedaling and legato studies (Repp, 1997) made it possible to compare individual differences across the two tasks. The correlation between individual average PRT (averaged across both excerpts) and key overlap time (averaged across three playing conditions) was 0.52 (n.s.). With K.S. omitted, however, the correlation reached significance ($r = 0.67$, $p < .05$). K.S. was the only pianist who had substantially longer PRTs than key overlaps. Consistent individual differences may reflect different perceptual tolerances for overlap between successive sonorities. Alternatively, since both long PRTs and long key overlaps do result in a more beautiful legato, they may represent desirable technical skills that have not been mastered by even some rather advanced pianists. Presumably, both temporal intervals are the more difficult to control the longer they are; the easier strategy is to aim for synchrony or near-synchrony of key depressions and either key or pedal releases. However, the availability of long PRTs and key overlaps enables skilled pianists to vary these times systematically for expressive purposes, and this may be one of the secrets of advanced legato technique.

From a practical perspective, the timing of pedal depressions seems less important than that of pedal releases. The raising of the pedal during a pedal change damps the sympathetic vibrations of strings whose keys are not depressed, but it does not affect the tones of the chord that is being played. There may be a small loss in the timbral richness of the chord during the pedal change, but it is doubtful that this change is perceptible. Once the pedal is depressed again, weak sympathetic vibrations may resume while the chord continues to decay. Although the precise duration of the pedal change time is not likely to be of great perceptual significance, there is nothing to be gained from unduly prolonging it.

Of course, it is important to depress the pedal before the keys of a chord are released. Contrary to expectations, however, the earliest key release did not seem to exert a significant constraint on pedal depression and pedal change times.[7] Thus, it seems more likely that the timing of the key release is constrained by the pedal depression than the reverse. If the tempo gets so fast that key releases precede pedal depressions, regular legato pedaling is probably no longer possible. Future investigations will have to determine the accuracy of these speculations.

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[7] The data on this point were not presented in detail. However, the observations made on D.G.'s data (Fig. 3) are representative.

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