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Relational invariance of expressive microstructure across global tempo changes in music performance: An exploratory study

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Summary. This study addressed the question of whether the expressive microstructure of a music performance remains relationally invariant across moderate (musically acceptable) changes in tempo. Two pianists played Schumann's "Träumerei" three times at each of three tempi on a digital piano, and the performance data were recorded in MIDI format. In a perceptual test, musically trained listeners attempted to distinguish the original performances from performances that had been artificially speeded up or slowed down to the same overall duration. Accuracy in this task was barely above chance, suggesting that relational invariance was largely preserved. Subsequent analysis of the MIDI data confirmed that each pianist's characteristic timing patterns were highly similar across the three tempi, although there were statistically significant deviations from perfect relational invariance. The timing of (relatively slow) grace notes seemed relationally invariant, but selective examination of other detailed temporal features (chord asynchrony, tone overlap, pedal timing) revealed no systematic scaling with tempo. Finally, although the intensity profile seemed unaffected by tempo, a slight overall increase in intensity with tempo was observed. Effects of musical structure on expressive microstructure were large and pervasive at all levels, as were individual differences between the two pianists. For the specific composition and range of tempi considered here, these results suggest that major (cognitively controlled) temporal and dynamic features of a performance change roughly in proportion with tempo, whereas minor features tend to be governed by tempo-independent motoric constraints.

Introduction

When different artists perform the same musical composition, they often choose very different tempi. Even though each artist may be convinced that his or her tempo is right, and even though the composer may have prescribed a specific tempo in the score, there is in fact a range of acceptable tempi for any composition played on conventional instruments. The American composer Ned Rorem has expressed this well:

> Tempos vary with generations like the rapidity of language. Music's velocity has less organic import than its phraseology and rhythmic qualities; what counts in performance is the artistry of phrase and beat within a tempo. ... [The composer's] Tempo indication is not creation, but an afterthought related to performance. Naturally an inherently fast piece must be played fast, a slow one slow – but just to what extent is a decision for players. (Rorem, 1983, p. 326)

Guttmann (1932) measured the durations of a large number of orchestral performances and found substantial tempo variation across different conductors, for the same composition. In extreme cases, the fastest observed performance was about 30% shorter than the slowest one. In two recent studies, Repp (1990, 1992) compared performances by famous pianists of solo pieces by Beethoven and Schumann and in each case found a considerable range of tempi. The ratio of the extreme tempi was approximately 1:1.6 in each case, corresponding to a 37% difference in performance duration. Tempo differences among repeated performances by the same artist tend to be smaller, but may also be considerable (Guttmann, 1932; Repp, 1992), notwithstanding the observation of remarkable constancy for some artists or ensembles (Clynes & Walker, 1986).

Tempo varies not only between, but also within, performances. Even though no tempo changes may have been prescribed by the composer in the score, a sensitive performer will continuously modulate the timing according to the structural and expressive requirements of the music. This temporal modulation forms part of the *expressive microstructure* of a performance. Naturally, it is more pronounced in slow, expressive than in fast, motoric pieces. The problem of determining the global or baseline tempo of a highly modulated performance is addressed elsewhere (Repp, in press). In the present article the question of interest is whether overall tempo interacts with the pattern of expressive modulations.

The null hypothesis to be tested is that expressive microstructure (which on the piano includes not only successive tone-onset timing, but also simultaneous tone-onset asynchronies, successive tone overlap or separation, pedal timing, and successive, as well as simultaneous, intensity relationships) is *relationally invariant* across changes in tempo. What this implies is that a change in tempo amounts to multiplying all temporal intervals by a constant, so that all their relationships (ratios) remain intact. Nontemporal properties of performance (i.e., tone intensities) are likewise predicted to remain relationally invariant.

Relational invariance (also called *proportional duration*) is a key concept in studies of motor behavior (see Gentner, 1987; Heuer, 1991; Viviani & Laissard, 1991). It has been used as an indicator of the existence of a generalized motor program (Schmidt, 1975) having a variable rate parameter. Many activities have been examined from that perspective, and relational invariance has commonly been observed, even though stringent statistical tests may show significant deviations from strict proportionality (see Heuer, 1991). The deviations may result from the combination of more central and more peripheral sources of variability. Heuer (1991) conjectures that relational invariance is most likely to obtain when the motor behavior is "natural" (i.e., conforms to peripheral constraints) and "self selected" (i.e., not imposed by the experimenter). These conditions certainly apply to artistic music performance, especially when (as in the present study) it is slow and expressive, so that peripheral factors (i.e., technical difficulties) are minimized. Nevertheless, even such a performance has aspects (e.g., the relative asynchrony of chord tones or the relative overlap of *legato* tones on the piano) that are subject to peripheral constraints imposed by fingering, the spatial distance between keys, and the limits of fine motor control. The question of relational invariance thus may be asked at several levels of detail, and the answers may differ accordingly. In sheer complexity and degree of precision, expert musical performance exceeds almost any other task that may be investigated from a motor-control viewpoint (see Shaffer, 1980, 1981, 1984).

Few previous studies have looked into the question of relational invariance in music performance. Deviations from relational invariance seem likely when the tempo changes are large. Handel (1986) has pointed out that changes in tempo may cause rhythmic reorganization: A doubling or halving of tempo often results in a change of the level at which the primary beat (the *tactus*) is perceived; this changes the rhythmic character of the piece, with likely consequences for performance microstructure. Very fast tempi may lead to technical problems, whereas very slow tempi may lead to a loss of coherence. These kinds of issues may be profitably investigated with isolated rhythmic patterns, scales, and the like. When it comes to the artistic interpretation of serious compositions, however, such dramatic differences in tempo are rare. The tempi chosen cannot stray too far from established norms, or else the performance will be perceived as deviant and stylistically inappropriate. In this study, therefore, we shall be concerned only with moderate tempo variations that are within the range of aesthetic acceptability for the composition chosen. Still, as indicated above, this range is wide enough to make the question of relational invariance nontrivial.

Since different artists' performances of the same music differ substantially in their expressive microstructure ("interpretation"), as well as in overall tempo, it is virtually impossible to determine the relationship between these two variables by comparing recordings of different artists. Although many studies have demonstrated that individual performers are remarkably consistent in reproducing their expressive timing patterns across repeated performances of the same music, these performances are generally also very similar in tempo (e.g., Seashore, 1938; Shaffer, 1984; Shaffer, Clarke, & Todd, 1985; Repp, 1990, 1992). Where substantial differences in tempo do occur, underlying changes in interpretation (i.e., in the cognitive structure underlying the performance) cannot be ruled out (e.g., Shaffer, 1992; Repp, 1992). In other words, the change in tempo may have been caused by a change in interpretation, rather than the other way around. Clearly, artists can change their interpretation at will, and with it the tempo of a performance. The question posed in the present study was whether a change in tempo *necessitates* a change in expressive microstructure. So an experimental approach was taken, in which the same artist was asked to play a piece at different tempi without deliberately changing the interpretation. The resulting performance data were analyzed and compared. This approach was supplemented by a perceptual test in which the tempo of recorded performances was artificially modified and the result was judged by musically trained listeners.

One previous study that directly addressed the hypothesis tested here was conducted by Clarke (1982), following preliminary, but inconclusive, observations by Michon (1974). Clarke examined selected sections of performances of the highly repetitive piano piece, "Vexations," by Erik Satie, played by two pianists who had been instructed to vary the tempo. The timing patterns (tone inter-onset intervals, or IOIs) of the same music at six different tempi were compared, and a significant interaction with tempo was found. The interaction was in part due to a narrowing of the tempo range in the course of the excerpt, but a significant effect remained after the tempo drift was removed statistically. Subsequent inspection of the data suggested to Clarke that the pianists had changed their interpretation of the grouping structure across tempi. At least one pianist produced more groups at the slower tempo, where group boundaries were identified by a temporary slowing down. Clarke also argued that group boundaries that were maintained tended to be emphasized more at the slower tempi.

While Clarke's interpretation seems plausible, the changes in the timing profiles across tempi were quite small and do not suggest different structural interpretations to this reader. Although there was more temporal modulation at the slower tempi, this is consistent with the hypothesis of relational invariance and may have accounted for the interaction with tempo. Such an interaction might not have appeared in log-transformed data.[1] Finally, even if it were

[1] For temporal intervals to be proportional at different tempi, their absolute differences must be larger at slow than at fast tempi. Clarke mentions that an initial analysis yielded "identical" results for raw and log-transformed data, but it is not clear whether that was also true in the later analysis just referred to.

true that the pianists changed their interpretations along with tempo, this may have reflected the extremely boring and repetitive nature of the music which, as the title says, is a deliberate harassment of the performer. So the generality of Clarke's conclusions is not clear. A very casual report of a follow-up study with a movement from a Clementi sonatina (Clarke, 1985) does not change the picture significantly.

In a study of piano performance at a simpler level, MacKenzie and Van Eerd (1990) found highly significant changes in tone IOIs as a function of tempo. Their pianists' task was to play scales as evenly as possible, and the range of tempi was very large. The IOI profiles observed were not due to musical structure or expressive intent, but to fingering; they became more pronounced as tempo increased. These kinds of motor constraints, though they become important in fast and technically difficult pieces, are likely to play only a minor role in slow, expressive performance, as studied here.

The immediate stimulus for the present study was provided by some informal observations reported by Desain and Honing (1992 a). They recorded a pianist playing a tune by Paisiello (the theme of Beethoven's variations on "Nel cor piú non mi sento") at two different tempi, M.M.60 and 90, and observed that the temporal microstructure differed considerably between the two performances. They also used a MIDI sequencer to speed up the slow performance and to slow down the fast one, and in each case they found that the altered performance sounded unnatural when compared to the original performance having the same tempo. On closer examination, the major differences between the two performances seemed to lie in the timing of grace notes, in the articulation of staccato notes, and in the spread (i.e., onset asynchrony) of chords, though the overall timing profiles also looked quite different.

In a subsequent paper, Desain and Honing (1992 b) developed a computer model for implementing changes in expressive timing. They distinguished four types of "musical objects": sequences of tones, chords, *appoggiature*, and *acciaccature*, the last two referring to types of grace notes. Each type of musical object is subject to different temporal transformation rules, which are applied successively within a hierarchical representation of the musical structure. In the first instance, these transformations represent changes along a continuum of degrees of expressiveness (i.e., deviations from mechanical exactitude) within a fixed temporal frame. However, the temporal changes within a larger unit propagate down to smaller units, effectively altering their tempo. Judging from their Figure 5, Desain and Honing propose that tone onsets within melodic sequences are stretched or shrunk proportionally as tempo changes, whereas the other three types of structure remain temporally constant or get "truncated" (in the case of chord asynchrony). Thus, these authors seem to suggest that relational invariance across changes in tempo does hold in a sequence of melody tones, but not in chords or ornaments. As to articulation (i.e., the overlap or separation of successive tones), they discuss three alternative transformations, without committing themselves. Their model is a system for implementing different types of rules, not a theory of what these rules might be. Nevertheless, their examples reflect some of their earlier informal observations.

The present study investigated not only timing patterns, but also tone intensities, another important dimension of expressive performance that has received much less attention in research so far. Todd (1992) has pointed out that an increase of tempo often goes along with an increase in intensity, which leads to the hypothesis that the overall dynamic level of a performance may be affected by a tempo change. MacKenzie and Van Eerd (1990) found such an increase in key-press velocity with tempo in their study of pianists playing scales. It is not clear whether any changes in intensity relationships should be expected across tempi, however. MacKenzie and Van Eerd found a subtle interaction, but the differences were not expressively motivated. The hypothesis investigated here was that intensity microstructure would remain relationally invariant across tempo changes, but that pianists might play louder overall at faster tempi. (If this latter effect were absent, the intensity pattern would be absolutely invariant.)

The present study aimed at providing some preliminary data bearing on these issues. The data were limited insofar as they came from a single musical composition played by two pianists, but they included a number of different measurable aspects of performance. The composition, Robert Schumann's "Träumerei," was selected because its expressive timing characteristics and acceptable tempo range were known from Repp's (1992) detailed analysis of 28 expert performances, and also because it is a slow, interpretively demanding, but technically not very challenging piece. It contains no *staccato* notes or ornaments, apart from a few expressive grace notes. Thus the main question was whether the expressive timing of the melody tones would or would not scale proportionally with changes in tempo. However, the tempo scaling of other performance aspects (grace notes, chord asynchrony, tone overlap, pedaling, dynamics) was of nearly equal interest. On the basis of the limited observations summarized above, it was expected that the overall timing and intensity profiles would exhibit relational invariance across tempo changes, whereas this might not be true for the more detailed temporal features. In the course of the detailed analyses, there were opportunities to make new (and confirm old) observations about the relation of musical structure and performance microstructure, some of which will be discussed briefly in order to characterize the nature of the patterns whose relational (non)invariance was investigated. A detailed investigation of structural factors is beyond the scope of this paper.

In addition to these performance measurements, a perceptual test was carried out along the lines explored by Desain and Honing (1992 a), to determine whether artificially speeded-up or slowed-down performances would sound odd in comparison with original performances having the same overall tempo. The results of this test will be described first, followed by the performance analyses.

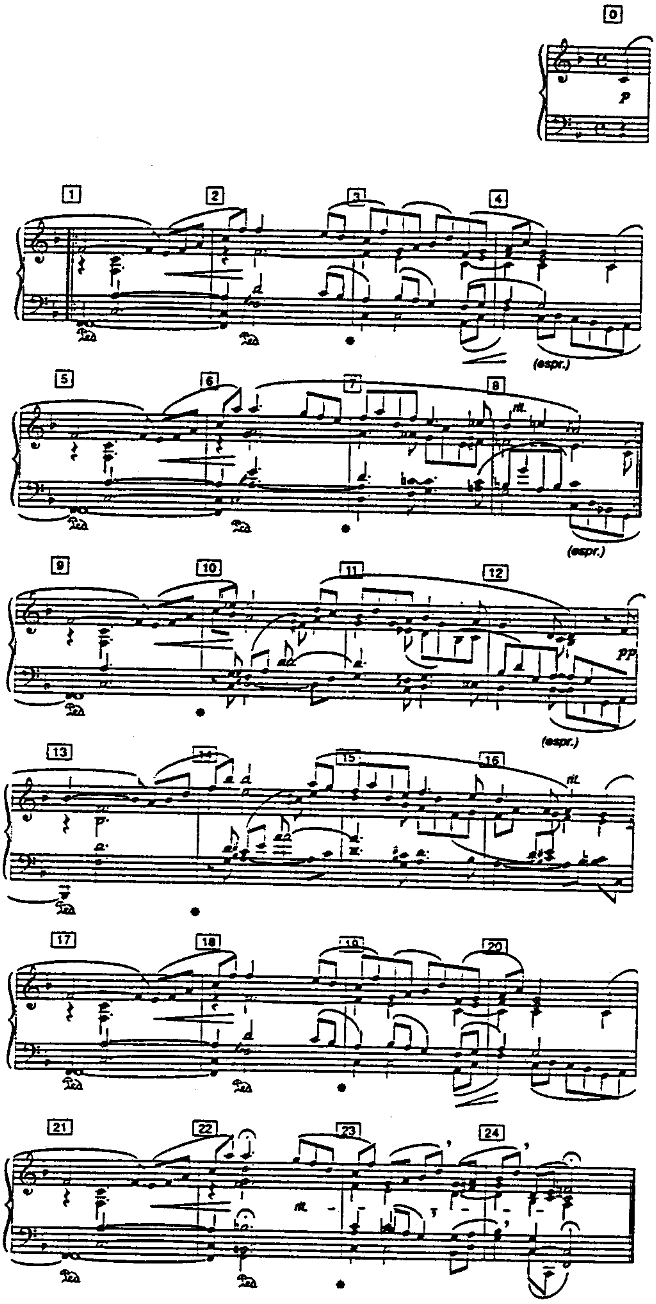

Fig. 1. The score of Schumann's "Träumerei," prepared with MusicProse software following the Clara Schumann edition (Breitkopf & Härtel). Minor discrepancies are due to software limitations. The layout of the computer score highlights parallel musical structures

Method

The music. The score of Schumann's "Träumerei" is shown in Figure 1; its layout highlights the hierarchical structure of the piece. The composition comprises three eight-bar sections, each of which contains two four-bar phrases which in turn are composed of shorter melodic gestures. The first section (bars 1–8) is repeated in performance. Each of the six phrases starts with an upbeat that (except for the one at the very beginning) overlaps with the end of the preceding phrase. Phrases 1 and 5 are identical and similar to phrase 6, whereas phrases 2, 3, and 4 are more similar to each other than to phrases 1, 5, and 6. Thus there are two types of phrase here. Vertically, the composition has a four-voice polyphonic structure. For a more detailed analysis, see Repp (1992).

Performers. The two performers were LPH, a professional pianist in her mid-thirties, and BHR (the author), a serious amateur in his late forties. Both were thoroughly familiar with Schumann's "Träumerei" and had played it many times in the past.

Recording procedure. The instrument was a Roland RD250S digital piano with weighted keys and sustain-pedal switch, connected to an IBM-compatible microcomputer running the Forte sequencing program. Synthetic "Piano 1" sound was used. The pianists played from the score and monitored the sound over earphones. The computer recorded each performance in MIDI format, including the onset time, the offset time, and the velocity of each key depression, as well as pedal on and off times. The temporal resolution was 5 ms.

Each pianist was recorded in a separate session. After some practice on the instrument, (s)he played the full piece (including the repeat of the first 8 bars) at her/his preferred tempo. Afterwards, (s)he listened to the beginning of the recorded performance and set a Franz LM-FB-4 metronome to what (s)he believed to be the basic tempo of the performance. The settings chosen by LPH and BHR were M.M.63 and 66, respectively. Subsequently, each pianist performed the piece at a slower and at a faster tempo. These tempi were chosen by the experimenter to be M.M.54 and 72 for LPH and M.M.56 and 76 for BHR. All these tempi were within the range observed in commercially recorded performances by famous pianists (Repp, 1992; in press). The desired tempo was indicated by the metronome before each performance; the metronome was turned off before playing started. The pianists' intention was to play as naturally and expressively as possible at each tempo; no conscious effort was made either to maintain or to change the interpretation across tempi.

Each pianist then repeated the cycle of three performances until three good recordings had been obtained at each tempo.[2] In these repeats, the medium (preferred) tempo was also cued by metronome. LPH's first performance was excluded because it showed signs of her still getting accustomed to the instrument, and an extra medium-tempo performance was added at the end of the session. BHR actually recorded five performances at each tempo, two in one session and three in another. Only the performances from the second session were used. Thus neither pianist's first performance was included in her/his final set of nine performances.

The MIDI data files were converted into text files and imported into a data analysis and graphics program (DeltaGraph Professional) for further processing. Tone interonset intervals (IOIs) in milliseconds were obtained by computing differences among successive tone onset times. Tone intensities were expressed in terms of raw MIDI velocities ranging from 0 to 127. In the middle range (which accommodated virtually all melody tones), a difference of 4 MIDI velocity units corresponds to a 1-dB difference in peak rms sound level (Repp, 1993).

Perceptual test and stimuli. The purpose of the perceptual test was to determine whether performances whose tempo has been artificially altered sound noticeably more awkward than unaltered performances. To reduce the length of the test, each performance was truncated after the third beat of bar 8; the cadential chord at that point was extended in duration to convey finality. Moreover, only the first two of each pianist's three performances at each tempo were used. From each of these 12 truncated original performances, two modified performances were generated by artificially speeding up or slowing down its tempo, so that its total duration matched that of an original performance at a different tempo by the same pianist. Thus, for example, LPH's first slow performance was speeded up to match the duration of the first medium performance, and was speeded up further to match the first fast performance. The tempo modification was achieved by changing

2 The pianists' accuracy in implementing the desired tempi will not concern us here; this issue is the subject of a separate paper (Repp, in press). Naturally, the three performances within each tempo category were not exactly equal in tempo.

the metronome setting in the Forte sequencing program, in relation to the baseline setting of M.M.100 during recording. (This setting was unrelated to the tempo of the recorded performance, but determined the temporal resolution.)

Each of the 12 original performances was then paired with each of two duration-matched modified performances, resulting in 24 pairs. The original performance was first in half the pairs and second in the other half, in a counterbalanced fashion. The pairs were arranged in a random order and were recorded electronically onto digital cassette tape. Performances within a pair were separated by about 2 s of silence, whereas about 5 s of silence intervened between pairs. The test lasted about half an hour.

Subjects and procedure. Nine professional-level pianists served as paid subjects. All but one were graduate students at the Yale School of Music, seven of them for a master's degree in piano performance and one for a Ph.D. degree in composition. They were tested individually in a quiet room. The test tape was played back at a comfortable intensity over Sennheiser HD420SL earphones. The subjects were fully informed about the nature and manipulation of the stimuli, and they were asked to identify the original performance in each pair by writing down "1" or "2", relying basically on which performance sounded "better" to them.

Results and discussion

Perceptual test

Average performance in the perceptual test was 55.6% correct. This was not significantly above chance across subjects, $F(1,8) = 2.91$, $p < .13$, though it was marginally significant across pairs of items, $F(1,11) = 5.08$, $p < .05$.[3] There was no significant difference between the scores for the two pianists' performances (though BHR's were slightly easier to discriminate) or for different types of comparisons. These results indicate that the tempo transformations did little damage to the expressive quality of the performances, and hence that there were probably no gross deviations from relational invariance, at least in the first eight bars.

Timing patterns at the preferred tempo

The performance aspect of greatest interest was the pattern of IOIs (the timing pattern or profile). Before examining the effects of changes in tempo on this aspect of temporal microstructure, however, it seemed wise to look at the timing profiles of the performances at the pianists' preferred (medium) tempi, to confirm that they were meaningful, representative, and reliable. This seemed particularly important in view of the fact that an electronic instrument had been used.

Figure 2 plots the onset-timing patterns averaged across the three medium-tempo performances of each pianist. The format of this figure is identical to that of Figure 3 in Repp (1992), which shows the Geometric-Average timing pattern of 28 different performances by 24 Famous Pianists (GAFP for short). The timing patterns of three related phrases are superimposed in each panel. (The two renditions of bars 1–8 were first averaged.) Interonset intervals longer than a nominal eighth-note one are shown as *plateaus* of equal eighth-note intervals.

The two pianists' average medium-tempo performances resembled both each other and the GAFP timing pattern. The correlations of the complete log-transformed IOI profiles ($N = 254$) were .85 between LPH and BHR, .88 between LPH and GAFP, and .94 between BHR and GAFP. Of course, these overall correlations were dominated by the major excursions in the timing profiles. A measure of similarity at a more detailed level was obtained by computing correlations only over the initial eight bars, which did not contain any extreme *ritardandi*. These correlations ($N = 130$) were .64 ($p < .0001$) between LPH and BHR, .77 between LPH and GAFP, and .83 between BHR and GAFP.[4] Clearly, both pianists' performances were reasonably representative in the sense that they resembled the average expert profile, even though they were only moderately similar to each other at a detailed quantitative level.

Each pianist also showed high individual consistency in terms of timing patterns both within and between the three performances at her/his preferred tempo. Thus the average correlation among the three complete medium-tempo performances was .91 for LPH and .95 for BHR. For the initial eight bars the corresponding correlations were .90 for both LPH and BHR. Needless to say, the timing patterns of the two renditions of bars 1–8 within each performance were also extremely similar.

Furthermore, as can be seen in Figure 2, both LPH and BHR produced very similar timing profiles for the identical phrases in bars 1–4 and 17–20 (left-hand panels); LPH played the whole phrase slower in bars 17–20, whereas BHR slowed down only in bar 17. Both pianists also showed similar timing patterns for the analogous phrases in bars 9–12 and 13–16 (right-hand panels), which diverged substantially only at the end, because of the more pronounced *ritardando* in bar 16, the end of the middle section. The structurally similar phrase in bars 5–8 (right-hand panels) again showed a similar pattern; apart from slight differences in overall tempo, major deviations from the pattern of the other two phrases occurred only in the second bar, where the music in fact diverges (cf. Figure 1), and also in the fourth bar for BHR, who emphasized the cadence in the soprano voice and treated the phrase-final bass voice as more transitional than did LPH. Finally, bars 21–24 (left-

[3] These values represent the grand mean effects in one-way ANOVAs on the average scores minus 50%, equivalent to one-sample t tests. The scond test was conducted on the average scores of pairs of pairs containing the same type of comparison in opposite order (e.g., LPH's first medium-tempo performance followed by the speeded-up version of her first slow performance, and the speeded-up version of her second slow performance followed by her second medium-tempo performance).

[4] All correlations reported include multiple data points for IOIs longer than one eighth note (cf. Fig. 2), which is equivalent to weighting longer IOIs in proportion to their duration. This seems a defensible procedure in comparing profiles, and omission of these extra points had a negligible effect on the magnitude of the correlations. However, in the ANOVAs reported further below, only a single data point was used for each long IOI, so as not to inflate the degrees of freedom for significance tests.

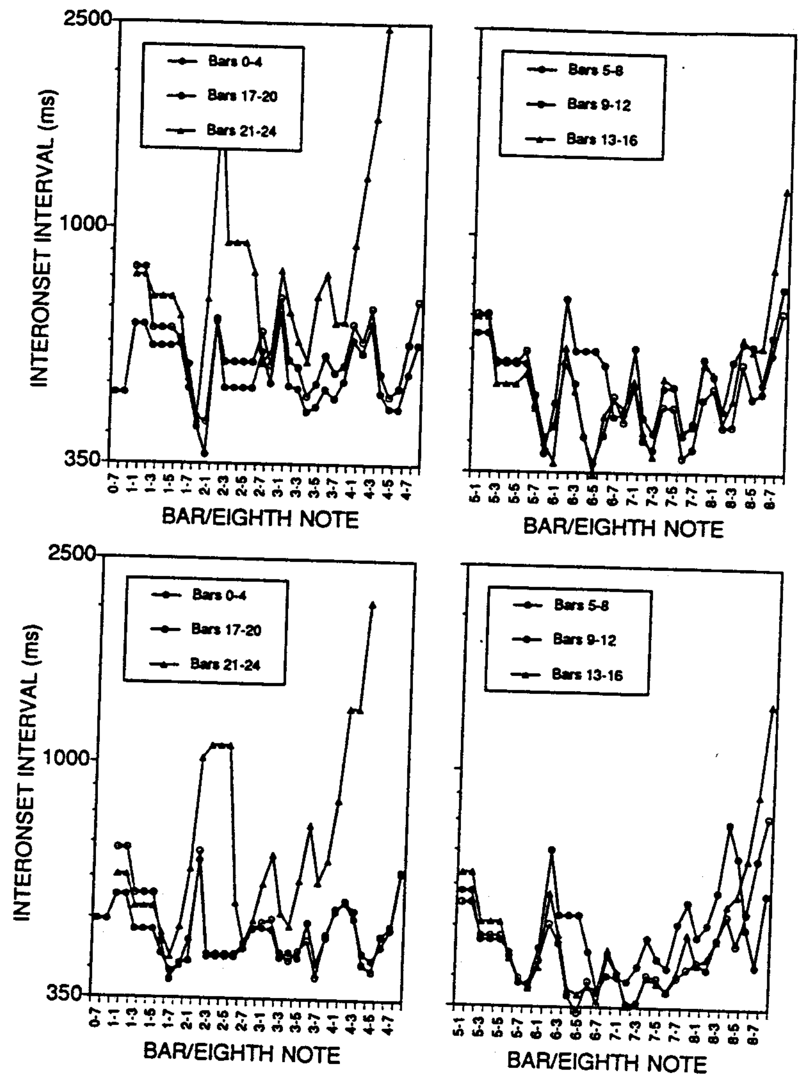

Fig. 2. Eighth-note IOIs as a function of metric distance, averaged across the three medium-tempo performances of each pianist (top: LPH; bottom: BHR). Structurally identical or similar phrases are overlaid in left- and right-hand panels

hand panels) retained the qualitative pattern of bars 1–4, but included substantial lengthening due to the *fermata* and the final grand *ritardando*.[5]

Many additional comments could be made about the detailed pattern of temporal variations and their relation to the musical structure, but such a discussion may be found in Repp (1992) and need not be repeated here. Instead, we now focus on the comparison among the three tempo conditions.

Effects of tempo on global timing patterns

A first question was whether the pianists were as reliable in their timing patterns in the slow and fast conditions as at the medium tempo. After all, they had to play at tempi they would not have chosen themselves. The average overall between-performance correlations within tempo categories for LPH were .88 (slow) and .91 (fast), as compared to .91 (medium); and for BHR they were .95 (slow) and .94 (fast), as compared to .95 (medium). Thus the pianists were just about as reliable in their gross timing patterns at unfamiliar tempi as at the familiar tempo. Computed over bars 1–8 only, the correlations were .83 (slow) and .86 (fast) versus .90 (medium) for LPH, and .89 (slow) and .86 (fast) versus .90 (medium) for BHR. At this more detailed level, then, there is an indication that the pianists were slightly more consistent when they played at their preferred tempo. Clearly, however, they produced highly replicable timing patterns even at novel tempi.

We come now to the crucial question: Were the timing profiles at the slow and fast tempi similar to those at the medium tempo? First, the correlational evidence. The average of the 27 between-tempo correlations (3×3 for each of three pairs of tempo categories) across entire performances for LPH was .90, which was the same as her average within-tempo correlation. For BHR, the analogous correlations were .94 and .95, respectively. At the more

[5] Two differences between LPH and BHR are worth noting here: LPH prolonged the interval preceding the *fermata* chord much more than did BHR, and she did not implement the gestural boundary (i.e., the comma in the score) in bar 24, executing a continuous *ritardando* instead. Contrary to the score, LPH generally arpeggiated the chord under the *fermata*; hence the long IOI, which was measured to the last (highest) note of the chord.

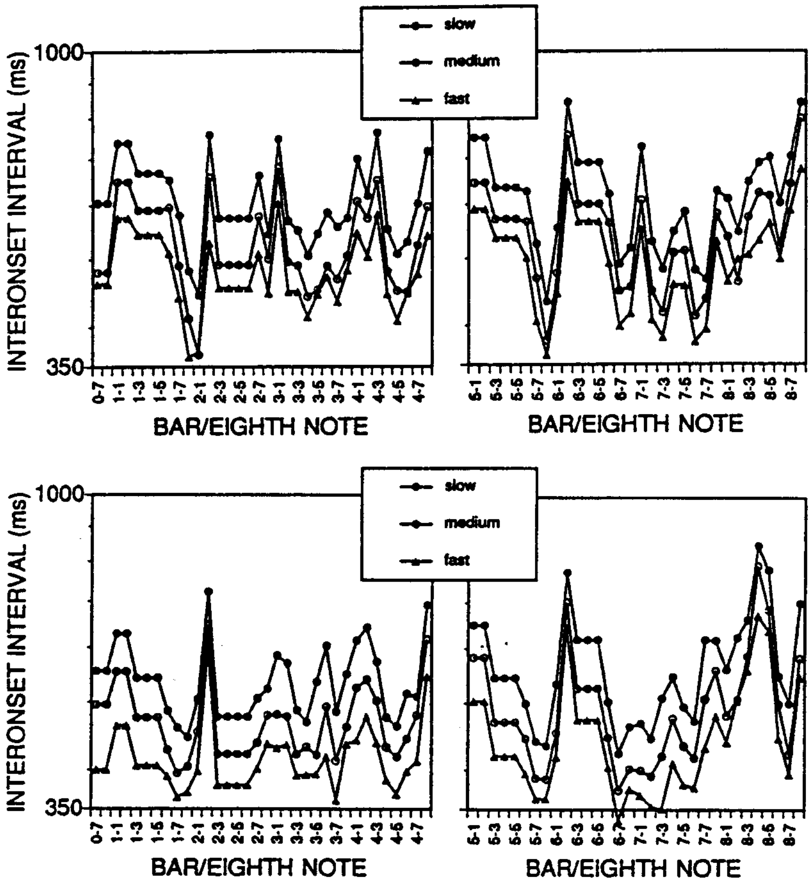

Fig. 3. Eighth-note timing profiles for the initial eighth bars (first renditions) at three different tempi, averaged across the three performances within each tempo category (top: LPH; bottom: BHR)

detailed level of bars 1–8, the correlations were both .86 for LPH, and .87 versus .88 for BHR. Thus, between-tempo correlations were essentially as high as within-tempo correlations.

If, as is predicted by the relational-invariance hypothesis, the intervals at different tempi are proportional, then the average timing profiles should be parallel on a logarithmic scale. This is shown for the first rendition of bars 1–8 in Figure 3. There is indeed a high degree of parallelism between these functions; the few local deviations do not seem to follow an interpretable pattern. These data thus seem consistent with the hypothesis of a multiplicative rate parameter (which becomes additive on a logarithmic scale).

Nevertheless, further statistical analysis revealed that there were some reliable changes in temporal profiles across tempi. Analyses of variance (ANOVAs) were first conducted on each pianists' complete log-transformed IOI data, with IOI (214 levels; see footnote 4) and tempo (3 levels) as fixed factors, and individual performances nested within tempi (3 levels) as the random factor. If the log-transformed timing profiles are strictly parallel, then the interaction of IOI with tempo should be nonsignificant. In other words, the between-tempo variation in profile shape should not significantly exceed the within-tempo variation. For LPH, this was indeed the case, $F(426,1278) = 1.03$. For BHR, however, there was a small, but significant, interaction, $F(426,1278) = 1.55$, $p < .0001$. Moreover, when similar analyses were conducted on bars 1–8, corresponding to the excerpts used in the perceptual test (though with all three performances at each tempo included), the interaction of IOI with tempo was significant for both LPH, $F(96,288) = 1.57$, $p < .003$, and BHR $F(96,288) = 1.77$, $p < .0003$. Additional analyses confirmed that BHR showed subtle changes in timing pattern with tempo throughout most of the music, whereas LPH showed no statistically reliable changes with tempo except at the very beginning of the piece.[6]

Yet another way of analyzing the data revealed, however, that LPH did show some systematic deviations from relational invariance, after all. For pairs of tempi, the log-transformed average IOIs at the faster tempo were subtracted from the corresponding IOIs at the slower tempo, and the correlation between these differences and the IOIs at the slower tempo was examined. The relational-invariance hypothesis predicts that the log difference (i.e., the ratio) between corresponding IOIs should be constant, and hence the correlation with IOI magnitude should be zero. However, LPH showed a highly significant positive correlation between medium-fast differences and medium-tempo IOIs, $r(252) = .50$, $p < .0001$, which indicates that long IOIs changed proportionately less than short IOIs. BHR showed a similar, but smaller, tendency, which was nevertheless significant, $r(252) = .18$, $p < .01$. Between the slow and medium tempi, LPH showed a weaker tendency in

[6] One possible reason why LPH showed no significant interactions is that her tempo variation within tempo categories was greater than that of BHR (see Repp, in press), so that the separation of within-tempo and between-tempi variation was less clear in her data.

the opposite direction, whereas BHR showed no significant correlation. Very similar results were obtained for bars 1–8 only; thus the correlations did not derive solely from the very long IOIs. Relational invariance evidently held to a greater degree between the slow and medium tempi than between the medium and fast tempi.

Thus there is statistical evidence that relational invariance did not hold strictly, as observed also by Heuer (1991) in his discussion of simpler motor tasks. Still, the timing patterns were highly similar across the different tempi, and the differences that did occur do not suggest different structural interpretations. Moreover, they were not sufficiently salient perceptually to enable listeners to discriminate original performances from performances whose tempo had been modified artificially. (Since there was no evidence that changes with tempo were greater later in the piece than at the beginning, the results of the perceptual test for bars 1–8 can probably be generalized to the whole performance.) It seems fair to conclude, then, that relational invariance of timing profiles held *approximately* in these performances.

Grace-note timing patterns

The analysis so far has focused on eighth-note (and longer) IOIs only. However, "Träumerei" also contains grace notes. The question of interest was whether the timing of the corresponding tones also changed proportionally with overall tempo.

There are two types of grace notes in the piece. Those of the first type, notated as small eighth notes, are important melody notes occurring during major *ritardandi*. The slowdown in tempo lets them slip in without disturbing the rhythm. One of these notes occurs in bar 8 (between the fourth and fifth eighth notes); the other is the upbeat to the recapitulation in bar 17 (following the last eighth note in bar 16). The other type, notated as pairs of small sixteenth notes, represents written-out left-hand *arpeggi* (bars 2, 6, and 18) and is played correspondingly faster. While proportional scaling of the first, slow type was to be expected because they are essentially part of the expressive timing profile, the prediction for the second type was less clear. However, neither type is readily classifiable in terms of Desain and Honing's (1992b) *appoggiatura–acciaccatura* distinction.

Several ANOVAs were conducted on the log-transformed IOIs defined by these grace notes. Separate analyses of bars 8 and 16 included three IOIs: the preceding eighth-note IOI and the two parts of the eighth-note IOI bisected by the onset of the grace note. In neither case was there a significant interaction of IOI with tempo.[7] Thus the timing of these grace notes was scaled proportionally with changes in tempo. LPH and BHR differed in their timing patterns: in bar 8, the grace note occupied 68% (LPH) versus 57% (BHR) of the fourth eighth-note IOI; in bar 16, it occupied 55% (LPH) versus 37% (BHR) of the last eighth-note IOI. BHR thus took the grace-note notation somewhat more literally than did LPH.

Bars 2 and 18 were analyzed separately from bar 6, which involved different pitches (cf. Figure 1), though the timing patterns were found to be very similar. In each case there were three IOIs, defined by the onset of the second eighth note in the right hand, the onsets of the two grace notes in the left hand, and the onset of the highest note of the chord in the right hand. In no case was there a significant interaction of IOI with tempo.[8] Thus, even for these *arpeggio* grace notes, relational invariance seemed to hold. There were again individual differences between the two pianists: in bars 2, 6, and 18, the two grace notes together took up 68% (LPH) versus 79% (BHR) of the second eighth-note IOI, while the second grace note occupied 63% (LPH) versus 69% (BHR) of the grace-note interval. Both pianists maintained their individual patterns across bars 2, 6, and 18. Both individual timing patterns are within the range of typical values observed in Repp's (1992) analyses of famous pianists' performances.[9]

Chord asynchronies

One of the factors that might enable listeners to discriminate between a slowed-down fast performance and an originally slow one is that the asynchronies among nominally simultaneous tones are enlarged in the former. It was surprising, therefore, that there was no indication in the perceptual data that slowed-down fast performances sounded worse than speeded-up slow ones. There is no obvious reason why unintended vertical asynchronies (i.e., purely technical inaccuracies) should scale with tempo. However, asynchronies that are intended for expressive purposes (cf. Vernon, 1937; Palmer, 1989) may possibly increase as tempo decreases. Rasch (1988) reports such a tendency for asynchronies in ensemble playing.

A complete analysis of asynchronies was beyond the scope of this paper. Instead, the analysis focused on selected instances only. One good candidate was the four-tone chord near the beginning of each phrase (see Figure 1). This chord occurs eight times during the piece, seven times in identical form in F major and once (bar 13) transposed up a fourth to B-flat major. It does not contain any melody tones, which eliminates one major motivation for expressive asynchrony (cf. Palmer, 1989). However, it is technically tricky because it involves both hands in interleaved fashion: The first and third tones (numbered from top to bottom) are taken by the right hand, while the second and fourth tones are taken by the left hand. In addition to unintended asynchronies that may be caused by this physical constellation, planned asynchronies may be involved in the proper *voicing* of the chord, which is a sonority of expressive importance.

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7 In bar 8 BHR showed a triple interaction of rendition (first vs. second playing), IOI, and tempo, $F(4,12) = 7.73$, $p < .003$, due to more even timing of the grace note in the first than in the second rendition, at the slow tempo only.

8 BHR showed a marginally significant (but not easily characterizable) triple interaction with rendition in bar 6, $F(4,12) = 3.42$, $p < .05$.

9 In terms of the IOI ratios plotted in Repp's (1992) Figure 11, the respective coordinate values are approximately 0.5 and 0.6 for LPH, and 0.25 and 0.45 for BHR.

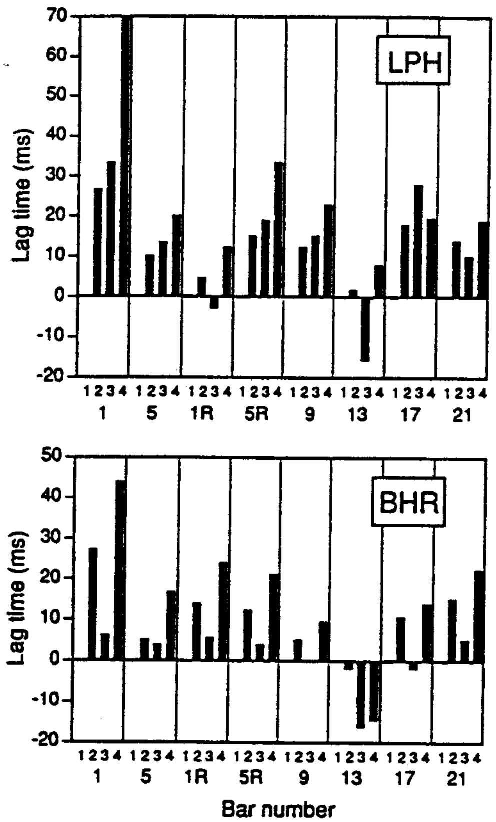

Fig. 4. Chord asynchronies relative to the highest tone, averaged across all tempi. The bars for each chord show lag times for tones 2–4 (in order of decreasing pitch) relative to tone 1. R after a bar number stands for *repeat*

For each of the eight instances of the chord in each performance, the IOIs for the three lower tones (Tones 2–4) were calculated in relation to the highest tone (Tone 1).[10] Lag times were positive, whereas lead times were negative. The untransformed IOIs were subjected to separate ANOVAs for each pianist, with the factors rendition (i.e., the 8 occurrences of the chord), tone (3), and tempo (3); performances (3, nested within tempo) were the random variable. The question here was whether the IOIs changed at all with tempo.

The ANOVA results were similar for the two pianists. Both LPH, $F(1,6) = 70.94$, $p < .0003$, and BHR, $F(1,6) = 84.71$, $p < .0002$, showed a highly significant grand mean effect, indicating that the average IOI was different from zero: The three lower tones lagged behind the highest tone by an average of 16.9 ms (LPH) and 9.6 ms (BHR), respectively; in addition, each pianist showed a rendition main effect (LPH, $F(7,42) = 3.58$, $p < .005$; BHR, $F(7,42) = 12.40$, $p < .0001$), a tone main effect (LPH, $F(2,12) = 12.80$, $p < .002$; BHR, $F(2,12) = 49.18$, $p < .0001$), and an interaction of rendition with tone (LPH, $F(14,84) = 2.56$, $p < .005$; BHR, $F(14,84) = 4.34$, $p < .0001$). However, no effects involving tempo were significant. In particular, there was no indication that lags were larger at the slow tempo. The high significance levels of the other effects shows that the data were not simply too variable for systematic effects of tempo to be found.

The systematic differences in patterns of asynchrony across renditions are of theoretical interest and warrant a brief discussion. They are shown in Figure 4, averaged across all performances. The mean lags for individual tones indicated that for both pianists the lowest (fourth) tone lagged behind more than the other two. For BHR, moreover, the third tone did not lag behind at all, on average. This was clearly a reflection of the fact that it was played with the same hand as the highest (first) tone. Both pianists showed the largest lag times in bar 1, which is perhaps a start-up effect of getting the feel of the instrument. For both pianists, the only rendition in which any lower tones preceded the highest tone was the one in bar 13, which is in a different key. The precedence of the third tone here may be due to the fact that it falls on a black key, which is more elevated than the white keys and hence is reached earlier by the thumb of the right hand. Apart from this exceptional instance, BHR maintained his characteristic 1-3-2-4 pattern across all renditions, though the magnitude of the lags varied somewhat. LPH was more variable, showing an average 1-2-3-4 pattern in four renditions, a 1-3-2-4 pattern in two, and a 1-2-4-3 pattern in one.

It could well be that the chord asynchronies just analyzed did not vary with tempo because they were not governed by expressive intent, only by fingering and hand position. The chord examined did not contain any melody tones and thus did not motivate any highlighting of voices through deliberate timing offsets. Therefore, a second set of chords was examined. The tone clusters on the second and third eighth notes of bars 10 and 14 (see Fig. 1) also contain four tones each (three in one instance), but all of them have melodic function. The soprano voice completes the primary melodic gesture; the alto voice splits off into a counterpoint; the tenor voice enters with an imitation of the primary melody, accompanied by the bass voice, which has a mainly harmonic function. Thus the relative salience of the voices may be estimated as 1-3-2-4, which may well be reflected in a sensitive pianist's relative timing of the tone onsets. Unlike the chords examined previously, tones 1 and 2 are played by the right hand, whereas tones 3 and 4 are played by the left hand. Since the highlighting of the tenor-voice entry (left hand) may be the performer's primary goal, the temporal relationship between the two hands may be the primary variable here.

This indeed turned out to be the case, though with striking differences between the two pianists. LPH changed her pattern of asynchronies radically (and somewhat inconsistently) with tempo in bar 10; otherwise, however, the patterns did not vary significantly with tempo. The main effects of the tone factor, on the other hand, were generally significant, indicating consistency in patterning for each chord.

The results are shown in Figure 5. As can be seen, LPH showed enormous asynchronies, which were almost certainly intended for expressive purposes. They alternated between two patterns. The left hand (tones 3 and 4) either

[10] The measurements were coarse because the 5-ms temporal resolution was poor, considering the small size of these intervals. However, the availability of repeated measurements within and across performances attenuated this problem considerably.

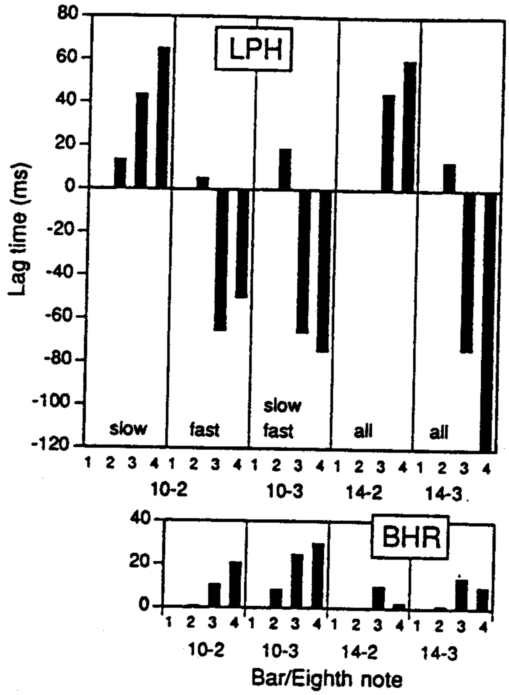

Fig. 5. Chord asynchronies in bars 10 and 14, averaged across all tempi except as noted. The second tone is absent in position 14-2

lagged behind or led the right hand (tones 1 and 2). The right-before-left pattern occurred in positions 10-2 (slow tempo) and 14-2. The left-before-right pattern occurred in positions 10-3 (at both slow and fast tempi) and 14-3, as well as in position 10-2 at the fast tempo. The medium-tempo patterns in positions 10-2 and 10-3 (not shown in the figure) were split among the two alternatives. The two tones in each hand were roughly simultaneous, except in position 14-3, where the lowest note occurred especially early. The net effect in bar 14 and, less consistently, in bar 10, was that the tenor and bass voices entered late but continued early, so that the first IOI in these voices was considerably shorter than the corresponding IOI in the soprano voice. This makes good sense: While the soprano voice slows down toward the end of a gesture, the tenor voice initiates the imitation with a different temporal regime. The discrepancy thus highlights the independent melodic strains.

The statistical analysis was conducted on the left-hand lag times only, because they showed the major variation. Owing to LPH's strategic changes with tempo in bar 10, there were highly significant interactions with tempo in the overall analysis of her data. A separate analysis on bar 14, however, revealed no effects involving tempo. The difference between positions 14-2 and 14-3 was obviously significant, as was the effect of tone $F(1,6) = 19.57$, $p < .005$ and the interaction of position with tone, $F(1,6) = 28.34$, $p < .002$.

BHR, on the other hand, showed a very different pattern. His asynchronies were much smaller and always showed a slight lag in the left hand, more so in bar 10 than in bar 14. His patterns were highly consistent but reveal little expressive intent, as they are comparable in magnitude to the asynchronies in the nonmelodic chord analyzed earlier. The statistical analysis on the left-hand lag times showed the difference between bars 10 and 14 to be highly reliable, $F(1,6) = 24.51$, $p < .003$. The tendency for the bass voice to lag behind the tenor voice in bar 10, but to lead it in bar 14, was reflected in a significant interaction, $F(1,6) = 12.66$, $p < .02$. No effect involving tempo was significant, however, Thus, neither pianist's patterns scaled with tempo. Relational invariance does not seem to hold at this level; instead, there is absolute invariance across tempi, except for the qualitative changes noted in some of LPH's data.

Tone overlap

Another detailed feature that was examined, again selectively, was tone overlap. MacKenzie and Van Eerd (1990), in their study of piano-scale playing, found that the absolute overlap of successive tones in *legato* scales decreased as tempo increased. At the slowest tempo, successive tones overlapped by about 15 ms, which decreased to near zero as tempo increased. Because of the expressive *legato* required in "Träumerei", and the slower rate of tones, larger overlaps were to be expected. The question was whether they got smaller as tempo increased. The measure of overlap was the difference between the offset time (key release) of one tone and the onset time (key depression) of the following tone in the MIDI data; it does not reflect the actual acoustical overlap of the tones, which depends on the decay time of the first tone following key release. A negative value indicates a gap between the tones (which may not be audible because of pedaling or acoustic overlap).

The passage selected for analysis was the ascending eighth-note melody in the soprano voice that occurs first in bars 1 and 2 and recurs in identical or similar form seven times during the piece (see Figure 1). Because of different fingering and an additional voice in the right hand, the instances in bars 9–10 and 13–14 were not included. Moreover, because overlap times varied wildly in the last interval of bar 22 (preceding the *fermata*) for both pianists, the data were restricted to the first four instances only (i.e., bars 1–2 and 5–6, and their repeats). Each of these consists of five consecutive eighth-notes, yielding four overlap times. The last two notes span the interval of a fourth in two instances (bars 1–2) and a major sixth in the other two (bars 5–6); otherwise, the notes are identical. The fingering is likely to be the same. The statistical analyses (on untransformed data) included bars as a factor, as well as renditions (here, strict repeats), tones, and tempo. Again, the question was whether the overlap times varied with tempo at all.

LPH's data were quite a surprise because her overlap times were an order of magnitude larger than expected. Not only did she play *legatissimo* throughout, but she often held on to the second and fourth tones through the whole duration of the following tone, which resulted in overlap times in excess of 1 s. Since these overlap times thus became linked to the regular eighth-note IOIs, it is not surprising that effects of tempo were found. The effects were not simple, however. The ANOVA showed all main effects and interactions involving bar, tone, and tempo (except for the interaction of bar with tone) to be significant. The data

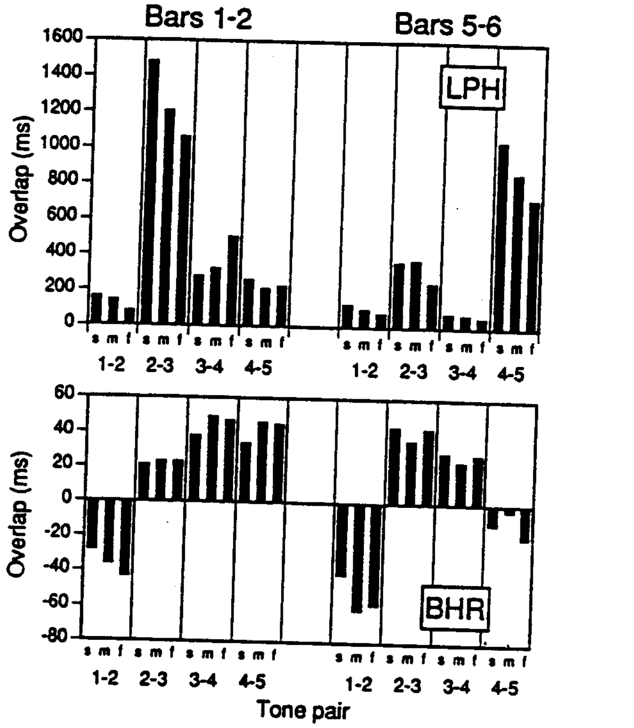

Fig. 6. Tone-overlap times in bars 1–2 and 5–6 at s(low), m(edium), and f(ast) tempi

corresponding to the triple interaction, $F(6,18) = 4.04$, $p < .01$, are shown in Figure 6. The data are averaged over renditions, which had only a main effect, $F(1,6) = 10.30$, $p < .02$, representing an increase in overlap with repetition.

Perhaps the most interesting fact about LPH's data is that the overlap pattern differed between bars 1–2 and 5–6 from the very beginning, even though the two tone sequences were identical up to last tone. There was slightly more overlap between the first two tones in bars 1–2 than in bars 5–6. While this may not be a significant difference, there is no question that the overlap between the following two tones was much greater in bars 1–2 than in bars 5–6. The same is true for the next two tones, although there is much less overlap in absolute terms. Finally, the situation is reversed for the last two tones, which show enormous overlap in bars 5–6, but much less in bars 1–2. The tempo effects within this striking interaction are fairly consistent (overlap decreasing with increasing tempo), except for the third and fourth tones in bars 1–2, whose overlap actually increases with tempo – an unexplained anomaly.

BHR's overlap times, in contrast to LPH's, were of the expected magnitude, and there was no significant effect involving tempo. However, the main effects of bar and tone, and the interaction of bar with tone, $F(3,18) = 24.90$, $p < .0001$, were all highly significant. As for LPH, the difference in final interval size affected the overlap pattern of the whole melodic gesture. BHR showed negative overlap (i.e., a gap camouflaged by pedaling) between the first two tones, which was larger in bars 5–6 than in bars 1–2. The overlap between the second and third tones was larger in bars 5–6, but that between the third and fourth tones was larger in bars 1–2. Finally, there was overlap between the last two tones in bars 1–2, but a small gap in bars 5–6, probably reflecting the stretch to the larger interval of a sixth. BHR's playing style thus can be seen to be only imperfectly *legato*, perhaps because of his less developed technique. Nevertheless, he was highly consistent in his imperfections, and his data suggest that they were independent of tempo.

Pedal timing

As the last temporal facet of these performances, we consider the timing of the sustain pedal. Although variations in pedal timing within tone IOIs probably had little, if any, effect on the acoustic output, they are of interest from the perspective of motor organization and control. The pianist must coordinate the foot movements with the hand movements, and this is usually done subconsciously, while attention is directed toward the keyboard.

A complete analysis of the pedaling patterns would lead too far here, as the pedal was used continuously throughout each performance.[11] The analysis focused on the opening motive of each phrase, specifically on the interval between the downbeat melody tone and the following four-note chord, whose highest tone was used as the temporal reference (see Figure 1). This quarter-note IOI, which occurred eight times in the course of each performance (in bars 1, 5, 1R, 5R, 9, 13, 17, and 21, where R stands for *repeat*), usually contained a pedal change (i.e., a pedal offset followed by a pedal onset) in both pianists' performances, though BHR's pedal offsets generally fell very close to the onset of the downbeat tone, often preceding it slightly. Exceptions were bars 1, 1R, and 9, which usually contained only a pedal onset, the previous offset being far outside the IOI or absent (at the beginning of the piece). Only the pedal onsets are marked in the score. The pedal serves here to sustain the bass note struck on the downbeat, which a small left hand needs to relinquish in order to reach its portion of the following chord. In bar 13, in fact, the bass note can be sustained only by pedaling, as it occurs in a lower octave.

The question of interest was whether, across the variations in tempo, the pedal actions occurred at a fixed time after the onset of the quarter-note IOI or whether their timing varied in proportion with tempo, so that they occurred at a fixed percentage of the time interval. Figure 7 shows the average quarter-note IOI durations (squares) at the three tempi in the different bars. As expected, there was generally a systematic decrease in IOI duration from slow to medium to fast tempo (LPH, $F(2,6) = 12.85$, $p < .007$; BHR, $F(2,6) = 88.25$, $p < .0001$). Both pianists also showed a highly significant main effect of bar on IOI duration (LPH, $F(7,42) = 21.36$, $p < .0001$; BHR, $F(7,42) = 47.38$, $p < .0001$): The longest IOIs occurred in bar 17 (the beginning of the recapitulation); LPH also had relatively long IOIs in bar 21 and short ones in bar 1, whereas BHR had relatively long IOIs in bar 13 (the pas-

[11] It is common in piano performance for the pedal to be used more frequently than is indicated in the score. Note also that the pedal in this instance was a simple foot switch that did not permit the subtlety of pedaling that is possible on a real piano.

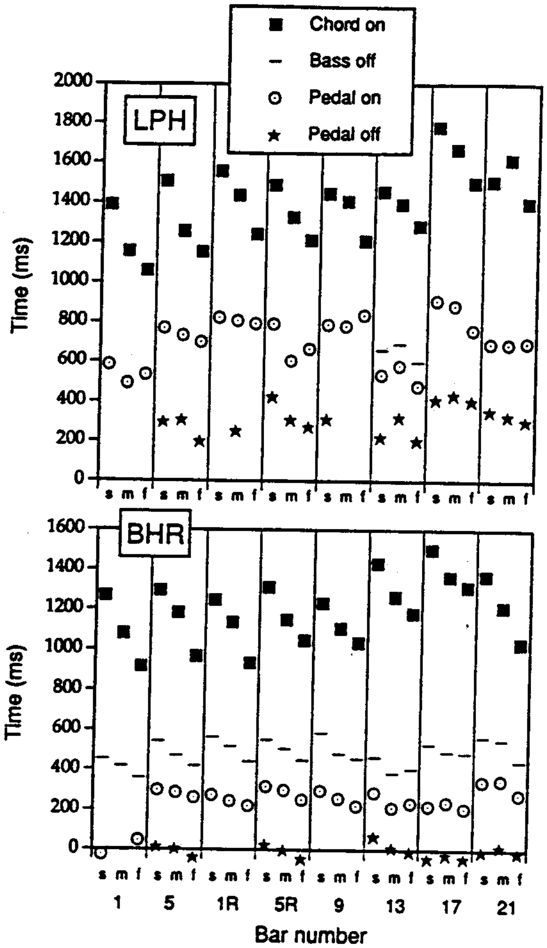

Fig. 7. Absolute pedal-offset and onset times and bass-tone offset times within the first (quarter-note) IOI in each of eight bars, at s(low), m(edium), and f(ast) tempi. Each IOI starts at 0 and ends with the onset of (the highest tone of) the chord. Missing symbols reflect incomplete or absent data

sage in a different key). There was a small interaction of tempo with bar for BHR only, $F(14,42) = 2.14$, $p < .03$.

Figure 7 also shows average pedal offset and onset times, as well as bass-tone offset times. The two pianists differed substantially in their pedaling strategies. LPH's pedal offsets (when present) occurred well after IOI onset, and her pedal onsets occurred around the middle of the IOI. BHR's pedal offsets, on the other hand, occurred at the beginning of the IOI, and his pedal onsets were relatively early also. Another striking difference between the two pianists is that LPH held on to the bass tone (as is indicated by the absence of dashes in the figure), except in bar 13 where this was physically impossible. BHR, on the other hand, despite his larger hands, always released the bass tone following the pedal depression.

For LPH, pedaling did not seem to vary systematically with tempo.[12] This was confirmed in ANOVAs on pedal offset and onset times, as well as on their difference (pedal-off time). None of these three variables showed a significant tempo effect or any interaction of tempo with bar. However, all three varied significantly across bars, $F(4,24) = 8.57$, $p < .0003$; $F(7,42) = 15.43$, $p < .0001$; $F(4,24) = 10.00$, $p < .0002$. For BHR, on the other hand, both pedal-offset times, $F(2,6) = 10.06$, $p < .02$, and pedal-onset times, $F(2,6) = 6.57$, $p < .04$, decreased as tempo increased, whereas pedal-off times did not vary significantly. All three varied significantly across bars, $F(4,24) = 6.09$, $p < .002$; $F(6,36) = 12.58$, $p < .0001$; $F(4,24) = 22.03$, $p < .0001$, even though the differences were much smaller than for LPH. Even more clearly than the pedaling times, BHR's bass-tone offset times varied with tempo, $F(2,6) = 27.26$, $p < .001$, and also across bars, $F(7,42) = 14.14$, $p < .0001$.

To determine whether BHR's timings exhibited relational invariance, they were expressed as percentages of the total IOI and the ANOVAs were repeated. Of course, the pedal-offset times, which varied around the IOI onset, could not be effectively relativized in this way, so that the tempo effect persisted, $F(2,6) = 9.36$, $p < .02$. The tempo effect on pedal-onset times, on the other hand, disappeared, $F(2,6) = 0.37$, whereas a tempo effect on pedal-off times emerged, $F(2,6) = 12.62$, $p < .008$. Thus BHR's data could be interpreted as either exhibiting relational invariance of pedal-onset times, or absolute invariance of pedal-off times. There was no question, however, that BHR's bass-tone-offset times scaled proportionally with tempo, as there was no tempo effect on the percentage scores, $F(2,6) = 0.71$. All relativized measures, on the other hand, continued to vary significantly across bars, $F(4,24) = 4.62$, $p < .007$; $F(6,36) = 17.81$, $p < .0001$; $F(4,24) = 23.86$, $p < .0001$; $F(7,42) = 18.90$, $p < .0001$. This was equally true for LPH's data.

In summary, these data do not offer much support for the hypothesis of relational invariance in pedal timing across tempo changes. LPH's data were highly variable. BHR's data are consistent with an alternative hypothesis – that the pedal off–on action (a rapid up–down movement with the foot) was independent of tempo, but was initiated earlier at the faster tempo. This earlier start may be a reflection of a general increase in muscular tension.

The results are much clearer with regard to the differences in pedaling times across bars. These effects are clearly not relationally invariant and thus must be caused by structural or expressive factors that vary from bar to bar. This may be the first time that such systematic variation has been demonstrated in pedaling behavior – an interesting subject for future studies.

Intensity microstructure

A detailed analysis of the intensity microstructure of the performances would lead too far in the present context. To verify, however, that both pianists showed meaningful

[12] LPH's pedaling times were much more variable than BHR's; this was also true within each tempo. The only substantial deviation for BHR occurred in bar 1, where pedal onset occurred at the beginning of the IOI in the absence of a preceding pedal offset. (In two instances at the medium tempo, however – not shown in the figure – there was a preceding pedal depression, and offset and onset times were similar to those in other bars.) Because of this deviation, BHR's bar 1 was omitted from further analyses of pedaling times. BHR never had a pedal offset near or within the IOI in bars 1R or 9, whereas LPH did have one some of the time; however, her following pedal-onset times did not seem to depend on whether there was a pedal offset nearby.

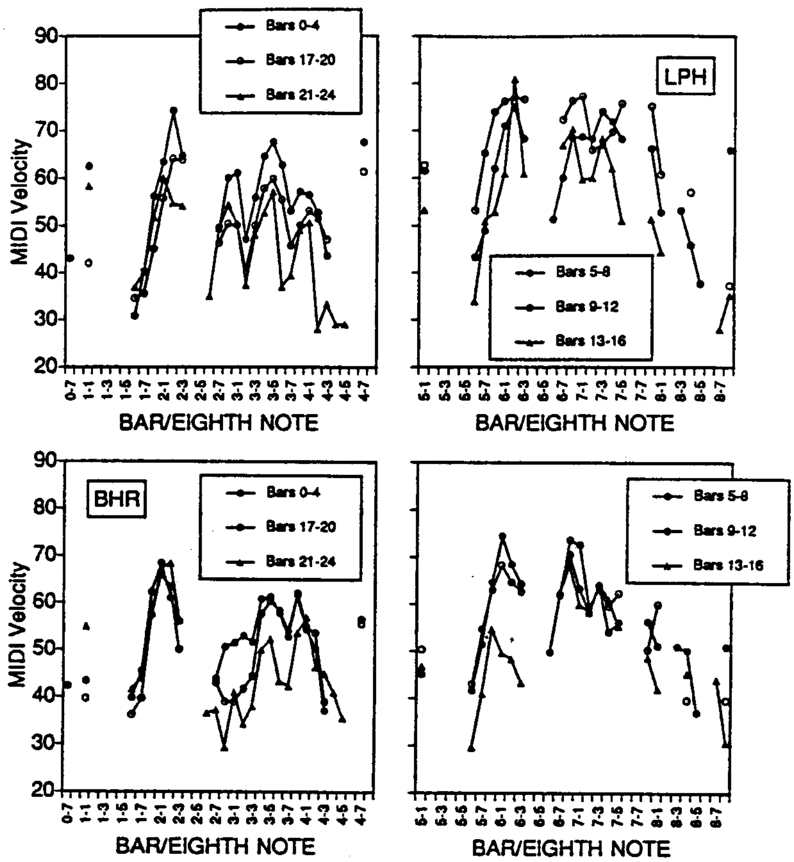

Fig. 8. Average MIDI velocity as a function of metric distance, averaged across three medium-tempo performances. Structurally identical or similar phrases are overlaid. Only adjacent eighth notes are connected

patterns of intensity variation, Figure 8 shows the intensity profiles (strictly speaking, MIDI-velocity profiles) of the melody notes (soprano voice) averaged across the three medium-tempo performances of each pianist (and averaged across the two renditions of bars 1–8). The format is similar to that of Figure 2, with corresponding phrases superimposed.

The intensity patterns were slightly more variable than the timing patterns. Nevertheless, both pianists showed structurally meaningful patterns that were similar across phrases of similar structure.[13] For example, the salient melodic ascent in bars 1–2, 5–6, and so on, always showed a steep rise in intensity which leveled off or fell somewhat as the peak was reached. The motivic chain during the second part of each phrase showed modulations related to the motivic structure, especially in the phrase type shown in the left-hand panels, and a steady *decrescendo* in the phrase type shown in the right-hand panels. Both pianists played bars 17–20 somewhat more softly than the identical bars 0–4, and ended the final phrase (bars 21–24) even more softly (left-hand panels). LPH, but not BHR, played bars 9–12 more strongly than bars 5–8 (right-hand panels). Both pianists played bars 13–16 more softly than bars 9–12; BHR especially observed the *pp* marking in bar 12 in the Clara Schumann edition (cf. Figure 1).

Given these fairly orderly patterns, the question of interest was: Did they vary systematically with tempo? Before this issue is addressed, however, it may be asked whether the average dynamic level was equal across tempi. According to Todd (1992), a faster tempo may be coupled with a higher intensity.

Figure 9 shows that this was indeed the case in the present performances. For both LPH and BHR, the average intensity of the soprano voice increased from slow to fast and from medium to fast tempo; there is no clear difference between slow and medium for LPH. The magnitude of the change is not large – about 2 MIDI units, which translates into about 0.5 dB (Repp, 1993). However, there is a second systematic trend in the data for both pianists. In the course of the recording session, the average intensity dropped by an amount equal to (BHR), or larger (LPH) than, that connected with a tempo change. There was also a tendency for the tempi to slow down across repeated performances (see Repp, in press), but that decrease was much smaller than the difference among the principal tempo categories. Both trends may reflect the pianists' progressive relaxation and adaptation to the instrument; possibly also fatigue. Finally, it is clear from Figure 9 that BHR played more softly, on the average, than LPH.[14]

Because of the within-tempo variation in average intensity, the between-tempo differences were nonsignificant, though they appeared to be systematic. For the same reason, the statistical assessment of variations in intensity patterns across tempi was somewhat problematic, for if that

[13] The intensity profiles of the expert performances studied by Repp (1992) are not available for comparison, as they are very difficult to determine accurately from acoustic recordings.

[14] This may be true only for the melody notes analyzed here, which indeed seemed to stand out more from among the four voices in LPH's performance.

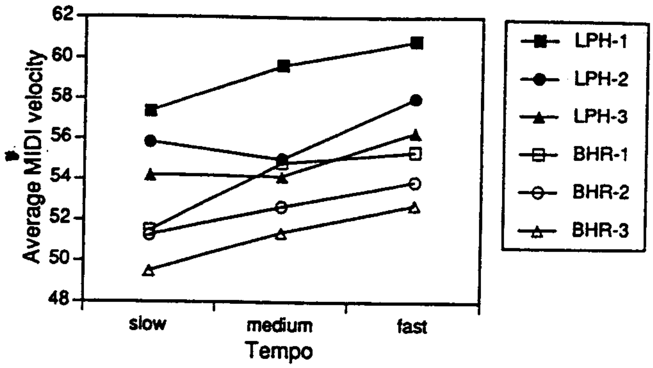

Fig. 9. Grand average MIDI velocity as a function of tempo, separately for each pianist's three performances at each tempo

variation was contingent on overall intensity (i.e., level of tension), there was no reason to expect it to be larger between, than within, tempi. ANOVAs were nevertheless carried out. Across all melody tones ($N = 166$), the interaction of tone with tempo fell short of significance for LPH, $F(330{,}990) = 1.13$, $p < .08$, and was clearly nonsignificant for BHR. Across the melody tones of the excerpt used in the perceptual test (bars 0–8, $N = 42$), the interaction of tone with tempo reached significance for LPH, $F(82{,}246) = 1.49$, $p < .01$, but remained clearly nonsignificant for BHR.[15]

Figure 10 shows the average intensity profiles for the melody tones in bars 1–8 at the three tempi for each pianist. The similarities among the three profiles are far more striking than the differences. For LPH, one source of the significant interaction of tone with tempo is evident at the very beginning: The dynamic change from the upbeat to the downbeat was far greater at the fast tempo than at the slow tempo. (Curiously, BHR showed the opposite.) On the whole, however, the intensity profiles remained invariant across tempi.

General discussion

The present study explored in a preliminary way the question of whether the expressive microstructure of a music performance remains relationally invariant across moderate changes in tempo. The results suggest that the onset timing and intensity profiles essentially retain their shapes (the latter being very nearly constant), whereas other temporal features are largely independent of tempo and hence exhibit local constancy rather than global relational invariance.

After a perceptual demonstration that a uniform tempo transformation does no striking damage to the expressive quality of performances of Schumann's "Träumerei", six specific aspects of the expressive microstructure were examined. The first and most important one was the pattern of tone-onset times. That pattern was highly similar across tempi, yet deviated significantly from proportionality. Although relational invariance did not hold perfectly, the deviations seemed small and not readily interpretable in

[15] Surprisingly, however, there was a significant tempo main effect for BHR, $F(2{,}6) = 12.78$, $p < .007$, suggesting that the within-tempo changes in overall intensity evident in Fig. 9 developed only later during his performances. For LPH, on the contrary, the between-tempi variation was conspicuously smaller than the within-tempo variation, $F(2{,}6) = 0.05$, $p > .95$, during the initial eight bars.

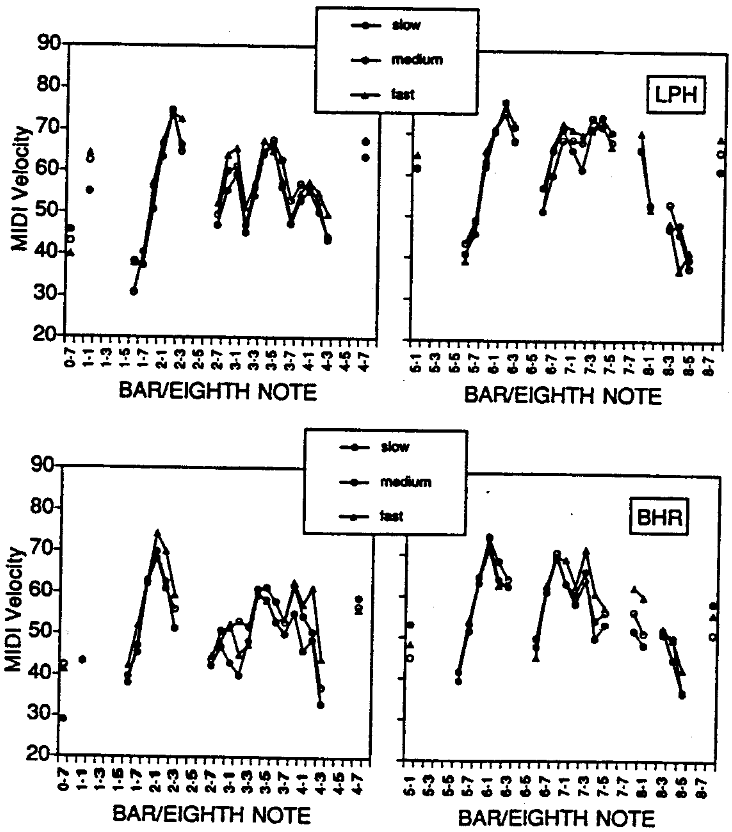

Fig. 10. Average MIDI velocity profiles for bars 0–8 at three different tempi

terms of structural reorganization. The second aspect examined was the timing of grace notes. Somewhat surprisingly, in view of the observations of Desain and Honing (1992a, b), that stimulated the present study, grace notes were timed in a relationally invariant manner across tempi. This may have been due to their relatively slow tempo and expressive function; the result may not generalize to ornaments that are executed more rapidly. The third aspect concerned selected instances of onset asynchrony among the tones of chords. These asynchronies did not change significantly with tempo, even when they were quite large and served an expressive function; they were apparently anchored to a reference tone. The fourth aspect was the overlap among successive *legato* tones. When this overlap was of the expected magnitude (pianist BHR), it was independent of tempo. For one pianist (LPH), the overlaps were unusually large and did vary with tempo. The fifth aspect examined was pedal timing, which did not seem to depend on tempo in a very systematic way and in any case had no audible effect. Finally, the intensity microstructure was studied. Although overall intensity increased somewhat with tempo, the detailed intensity pattern remained nearly invariant.

In no case were there striking deviations from relational invariance. Those features that were found not to scale proportionally with tempo were generally on a smaller time scale, so that artificially introduced proportionality (in the perceptual test) was difficult to detect. Because of the limited contribution of these details to the overall impression of the performances, it may be concluded that relational invariance of expressive microstructure held approximately across the tempi investigated here. This is consistent with the notion that musical performance is governed by a generalized motor program (Schmidt, 1975) or an interpretation that includes a variable rate parameter. Although there are good reasons for expecting the interpretation to change when tempo changes are large (Clarke, 1985; Handel, 1986), the tempo range investigated here could apparently accommodate a single structural interpretation.

All the microstructural patterns examined exhibited great, and highly systematic, variation as a function of musical structure, as well as clear individual differences between the two pianists. While the data on timing microstructure (including grace notes) are consistent with the detailed analyses in Repp (1992), the observations on chord asynchrony, tone overlap, pedaling, and intensity microstructure go well beyond these earlier analyses. However, since the focus of the present study was on the effects of tempo, the structural interpretation of microstructural variation has not been pursued in great detail. Suffice it to note once again the pervasive influence of musical structure on performance parameters and the astounding variety of individual implementations of what appear to be qualitatively similar structural representations.

Despite certain methodological parallels, the present study is diametrically opposed to the scale-playing experiment of MacKenzie and Van Eerd (1990), which essentially focused on pianists' inability to achieve a technical goal (viz., mechanical exactness). By contrast, the primary concern here was pianists' success in realizing the artistic goal of expressive performance. The relative invariances observed in timing and intensity patterns were cognitively governed, not due to kinematic constraints. However, both types of study have their justification and provide complementary information. At some of the detailed levels examined here (chord asynchronies, tone overlap) motoric constraints, such as fingering patterns, clearly had an influence. Thus, even within a slow, highly expressive performance, there are aspects that are governed to some extent by raw technique, and ultimately the technical skills that help an artist to achieve subtlety of expression may be the very same that help her/him to play scales smoothly. However, the technique serves its true purpose only in the context of an expressive performance and is therefore perhaps better studied in that context also.

The present study has limitations, the most obvious of which is that only a single piece of music was examined. Clearly, the character of "Träumerei" is radically different from that of Salieri's "Nel cor piú non mi sento", whose timing microstructure Desain and Honing (1992a) found to change considerably with tempo. "Träumerei" is slow, expressive, entirely *legato*, rhythmically vague, and contains few fast notes; even the grace notes are timed deliberately. The Salieri ditty, on the other hand, is moderately fast, requires a detached articulation and rhythmical precision, and contains a number of very fast grace notes (*acciaccaturas*), which may resist further reduction in duration. Clearly, it would be wrong to conclude from the present findings that expressive microstructure *always* remains invariant across tempo changes, even to a first approximation. Desain and Honing's (1992a) results, in spite of their informality, already seem to provide a counterexample.[16] So do perhaps Clarke's (1982, 1985) findings. The conclusion seems justified, however, that in *some* types of music relational invariance is maintained to a large extent. This music is probably the kind that carries expressive gestures on an even rhythmic flow. Rhythmically differentiated music containing many short note values, rests, and varied articulation (such as examined by Desain and Honing, 1992a) is probably much more susceptible to changes with tempo.

In fact, it would be both more precise and more cautious to say that relational invariance *can* be maintained in certain kinds of music. The present pianists, although they did not try very consciously to maintain their interpretation across tempi but instead attempted to play as naturally and expressively as possible, nevertheless refrained from changing their interpretation in the course of the recording session, whatever this may imply in an objective sense. In real-life music performance, on the other hand, changes in tempo are probably more often a consequence of a change in an artist's conception of the music than a deliberate change in the tempo as such. Tempo differences observed among different artists are often to be understood in this way. What the present findings imply, however, is that if different artists were forced to play at the same overall tempo, without being given time to reconsider their interpretation of the piece, their expressive microstructure

[16] Their data have been augmented in the meantime and are presented in Desain & Honing (1994).

would probably be just as different as it was before the tempi were equalized. In other words, tempo as such probably accounts only for a very small proportion of the variance among different performers' interpretations. Or, to put it yet another way, interpretation usually influences tempo, but tempo does not necessarily influence interpretation.

It will of course be desirable to employ a larger number of musicians in future studies, as well as a better instrument. The present two pianists' performances, however, seemed adequate for the purpose of the study. The fact that one pianist (BHR) was not professionally trained is not seen to be a problem, in view of the fact that his data were generally more consistent and less variable than those of the professional pianist, LPH. LPH's greater variability may be attributed to three sources: First, she had less time to adapt to the instrument; second, she had not played "Träumerei" recently; and third, as a professional artist, she was not obliged to obey the constraints of a quasi-experimental situation. BHR, on the other hand, was more familiar with the Roland keyboard, had practiced Schumann's "Kinderszenen" less than a year ago, and, as an experimental psychologist, was used to exhibiting consistent behavior in the laboratory.

In summary, the present findings suggest that for certain types of music it is possible to change the tempo within reasonable limits, either naturally in performance or artificially in a computer, without changing the quality and expression of a performance significantly. This suggests that the very complex motor plan that underlies artistic music performance contains something like a variable rate parameter that permits it to be executed at a variety of tempi while serving the same underlying cognitive structure. Various small-scale performance details, however, may be locally controlled and unaffected by the rate parameter. Thus local constancy appears to be nested within global flexibility in music performance.

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