964

Music Perception
Fall 1995, Vol. 13, No. 1, 39–57

Quantitative Effects of Global Tempo on Expressive Timing in Music Performance: Some Perceptual Evidence

BRUNO H. REPP
Haskins Laboratories

This study examines whether global tempo and expressive timing microstructure are independent in the aesthetic judgment of music performance. Measurements of tone interonset intervals in pianists' performances of pieces by Schumann ("Träumerei") and Debussy ("La fille aux cheveux de lin") at three different tempi show a tendency toward reduced relative variation in expressive timing at both faster and slower tempi, relative to the pianist's original tempo. However, this could reflect merely the pianists' discomfort when playing at an unfamiliar tempo. Therefore, a perceptual approach was taken here. Experimental stimuli were created artificially by independently manipulating global tempo (three levels) and "relative modulation depth" of expressive timing (RMD, five levels) in MIDI-recorded complete performances of the Schumann and Debussy pieces. Skilled pianists rated the quality of the resulting two sets of 15 performances on a 10-point scale. The question was whether the same RMD would receive the highest rating at all three tempi, or whether an interaction would emerge, such that different RMDs are preferred at different tempi. A small but significant interaction was obtained for both pieces, indicating that the listeners preferred a reduced RMD when the tempo was increased, but the same or a larger RMD when the tempo was decreased. Thus, they associated an increase in tempo with a decrease in (relative) expressive timing variation, which, in general agreement with the performance data, suggests that the two temporal dimensions are not independent.

Introduction

Whether and how certain object or event properties remain physically and/or perceptually invariant under various kinds of transformation is an important theoretical issue that pervades psychological research (see, e.g., Heuer, 1991; Perkell & Klatt, 1986; Warren & Shaw, 1985). The psychology of music is no exception (Hulse, Takeuchi, & Braaten, 1992). For example, it is well known that musical pitch intervals and melodies remain invariant under transformations of register (i.e., transposition); that is, they

Requests for reprints may be sent to Bruno H. Repp, Haskins Laboratories, 270 Crown Street, New Haven, CT 06511-6695. (e-mail: repp@haskins.yale.edu)

not only retain their frequency ratios in performance but are perceived as constituting the same melody. Some other forms of invariance in music are less well established or in doubt. Thus, although it may seem that rhythm should scale proportionally and remain perceptually invariant across changes in global tempo—and certainly the relative note values of simple rhythms can be reproduced and recognized across changes in tempo—several studies have suggested that subjective rhythmic organization changes with tempo (Handel, 1992; Handel & Lawson, 1983; Monahan & Hirsh, 1990; Parncutt, 1994), so that rhythms may not be executed in exactly the same way at different tempi, and listeners can find it difficult to match or recognize proportionally scaled rhythmic patterns when the tempo is changed substantially (Handel, 1993; Sorkin & Montgomery, 1991).

The present study is concerned with the relative invariance or noninvariance of expressive *timing microstructure* across global tempo changes in music performance. Timing microstructure consists of continuous modulations of the local tempo, resulting in unequal intervals between successive tone onsets, even if the corresponding notes have the same value in the score.[1] In the absence of timing microstructure, these tone interonset intervals (IOIs) would be identical; in an expressive performance, however, IOIs vary considerably and lawfully in a fashion determined both by the musical structure and the performer's interpretation and individuality (see, e.g., Gabrielsson, 1987; Palmer, 1989; Repp, 1992). *Relational invariance* (also called proportional scaling, ratiomorphic timing, or the homothetic principle; see Gentner, 1987; Heuer, 1991; Viviani & Laissard, 1991) is a key concept in research on timing control in skilled motor performance, although the tasks investigated have rarely been as complex as music performance. Relational invariance has been interpreted as evidence for a "generalized motor program" (Schmidt, 1975) that adjusts to tempo variations by means of a multiplicative rate parameter. Applied to expressive timing in music, this hypothesis implies that a change in global tempo results in a uniform compression or expansion of the timing pattern, leaving the ratios of successive IOIs constant.

Clarke (1982), following up on earlier observations by Michon (1974), has suggested that timing microstructure does not remain relationally invariant as the tempo of a performance changes, because of rhythmic reorganization. Although Clarke's data are weak (see Repp, 1994a), his discussion is reasonable: If global tempo changes are large enough to cause rhythmic reorganization, then this will probably be reflected in expressive timing and cause deviations from relational invariance. Desain and Honing (1994) presented stronger evidence for noninvariance of timing micro-

1. Timing microstructure, as defined here, does not include other temporal aspects of performance, such as asynchronies among the onsets of nominally simultaneous tones, overlaps among successive tones, and pedal timing. All these phenomena may be subsumed under the category of *temporal microstructure.*

structure in a piano piece played at three different tempi. However, they did not make clear what, if any, systematic principle underlay the deviations from invariance. Some of the clearest deviations occurred in the very brief IOIs associated with grace notes, where some perceptual or motoric lower limit may have been reached that prevented proportional scaling. The present study, in contrast, focused on the timing microstructure of relatively long IOIs, where such limits presumably do not play any role. More importantly, the present study was concerned with a relatively limited range of global tempi, over which a performer might reasonably be expected to maintain a particular rhythmic organization. Thus, although better demonstrations of *qualitative* changes in expressive timing as a function of changes in global tempo are needed, the research reported here focuses on the orthogonal dimension of *quantitative* changes in timing microstructure.

A qualitative change is one that affects the shape of the timing profile (IOI duration as a function of metrical position) and thus suggests a change in the underlying rhythmic structuring (e.g., a peak appears in the timing profile where previously there was none, or a peak disappears completely while other features remain relatively constant). Conversely, a quantitative change affects the magnitude of all peaks and valleys in the profile, suggesting relatively understated or exaggerated expression of the same underlying organization. Different degrees along this quantitative continuum are captured by the concept of *relative modulation depth* (RMD), which will be defined more precisely later. Note that *absolute* modulation depth (i.e., the absolute range of variation of the IOI durations) is likely to increase as global tempo decreases (i.e., as the average IOI duration increases). However, if relational invariance holds, then the variation increases simply by a multiplicative factor and the RMD remains constant. The question addressed in the present research, then, was whether the RMD does in fact remain constant when the tempo of a performance is changed. A less formal way of posing this question is: Does a change in overall tempo affect the degree of expressiveness of a performance (in the timing domain)?

SOME RELEVANT PERFORMANCE DATA

Repp (1994a) investigated whether relational invariance of expressive timing microstructure held in two pianists' performances of Robert Schumann's famous miniature, "Träumerei," played at three different tempi. Even though the timing profiles of all performances by the same pianist were highly similar, statistical analysis did show significant deviations from relational invariance. A subsequent regression analysis revealed systematic trends in these deviations, which are illustrated in Figure 1.[2]

2. This figure reflects analyses conducted after Repp (1994a) went to press. See Repp (1994b) for detailed information about the pianists' tempo choices.

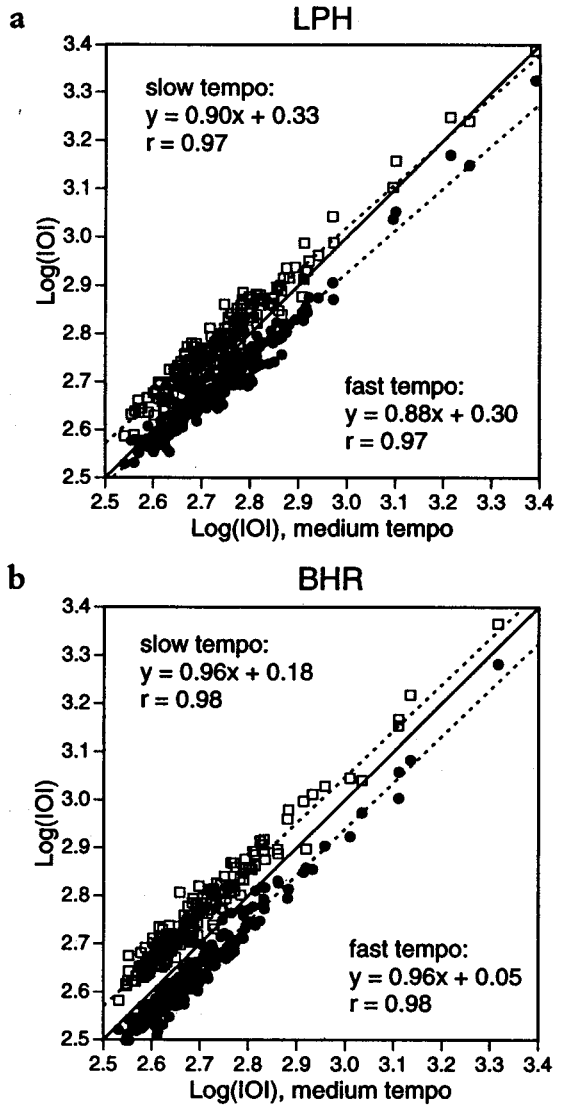

Fig. 1. Relationships between logarithms of interonset intervals (IOIs) at a medium tempo and at a fast and slow tempo, respectively, in performances of Schumann's "Träumerei" by two pianists (LPH and BHR). Data from Repp (1994a).

This figure plots the logarithms of the IOIs (n = 254) at the original preferred (medium) tempo against the logarithms of the same IOIs at faster and slower tempi, for each of the two pianists (LPH and BHR). To reduce random variability, the IOI durations were averaged over three performances at the same nominal tempo before the logarithms were computed. All IOIs

are nominally eighth notes, so that all variability is due to expressive timing alone. (Notationally longer IOIs in the music were subdivided into equal parts corresponding to eighth-note IOIs.) If relational invariance holds, then corresponding IOIs at two different tempi (T1, T2) should be proportional, so that $IOI_{T2} = cIOI_{T1}$, where c is a constant representing the tempo change. It follows that $\log(IOI_{T2}) = \log(c) + \log(IOI_{T1})$; that is, the relationship between the logarithms of the IOIs should be linear with a slope of one (parallel to the solid diagonal line in Figure 1) and the intercept $\log(c)$. However, the slopes of the dotted lines fit to the data in Figure 1 are significantly less than one, more so for LPH (Figure 1a), a professional pianist, than for BHR (Figure 1b), an amateur.[3] This alone would not be sufficient evidence for a deviation from proportionality because the slope of a regression line declines in proportion to the correlation between two variables. The relevant evidence is the fact that the slopes in Figure 1 are smaller than the correlations, implying that the standard deviations of the log(IOI) values were reduced at slow and fast tempi relative to medium tempo. (The slope divided by the correlation equals the ratio of the standard deviations.) In other words, when the tempo was increased, long IOIs decreased proportionally more than did short IOIs; when the tempo was decreased, long IOIs increased proportionally less than did short IOIs. In each instance, a change of tempo resulted in a reduced RMD, or a compression of the timing profile relative to the original tempo. The measure of RMD is the slope of the regression line divided by the correlation.

These observations suggest that expressive timing is not independent of global tempo. However, the nature of this dependence is surprising: Instead of there being a unidirectional change in "expressiveness" with tempo (with a relative decrease in expressiveness as the tempo gets faster being much more plausible than the reverse), it seems that the two pianists, especially LPH, played less expressively at both slow and fast tempi.[4] This could have a relatively trivial explanation, however: When a musician is asked to play at a tempo other than the preferred one, (s)he may feel less comfort-

3. The significance of the deviations of the slopes of the regression lines from unity was tested by computing the correlations between the log(IOI) values at the medium tempo and the differences between corresponding log(IOI) values at the fast and medium, or the slow and medium, tempi. These "difference correlations" were –0.50 and –0.43 ($p < .0001$), respectively, for LPH, and –0.18 ($p < .01$) and –0.21 ($p < .001$), respectively, for BHR.

4. Actually, the evidence for the slow tempo is somewhat ambiguous because there is noise in the data, as reflected in the imperfect correlations. Some or all of this noise may be due to imperfect motor control, the variability of which may be independent of tempo, or nearly so. If so, then this random variance will be larger relative to the systematic variance at a fast tempo than at a slow tempo, which leads to the prediction that the total variance of log(IOI) values should decrease with tempo. This is clearly counter to the finding of a smaller variance at the fast than at the medium tempo, but it is consistent with the smaller variance at the slow than at the medium tempo and may partially account for it.

able and/or may have to devote some attention to sticking to the prescribed tempo, which then may result in a restricted RMD.[5] Alternatively, it could be that there is an optimal (medium) tempo for a piece of music that somehow permits the greatest expressive freedom. Either of these possibilities may be called an "optimal tempo" hypothesis. The alternative hypothesis, which is not supported by the performance data, may be called "the faster, the less expressive." The null hypothesis, of course, is that relational invariance holds.

A PERCEPTUAL APPROACH

In order to circumvent possible artifacts due to performers' tempo preferences, the present study took a perceptual approach. If RMD tends to vary with global tempo in performance, then musicians should have corresponding expectations as listeners. These expectations were assessed here by varying global tempo and RMD *independently* in a performance, and by asking skilled pianists to evaluate the quality of the resulting versions. Given that a particular RMD is preferred at the medium (original) tempo, then it may be asked whether the same RMD is also preferred at a slower or faster tempo. Such a result would be consistent with the null hypothesis that expressive timing is relationally invariant across tempo changes. In that case, the variations in RMD observed in the "Träumerei" performances could be regarded as artifacts related to pianists' tempo preferences. Alternatively, the pianist judges might prefer a larger RMD at the slow tempo and a smaller RMD at the fast tempo. This would support the hypothesis of "the faster, the less expressive" and would suggest that only the reduction in RMD at a slow tempo is a performance artifact. Finally, it is conceivable that the perceptual judgments will mirror the performance data, with a smaller RMD being preferred at both a slow and a fast tempo. This would support the "optimal tempo" hypothesis. Statistically speaking, both of the latter findings represent an *interaction* between global tempo and RMD, whereas the null hypothesis predicts no interaction.

In his earlier related study, Repp (1994a) focused on performance measurements but also included a perceptual test. He took the first eight bars of each of the two pianists' "Träumerei" performances at the three tempi and changed their tempo artificially by stretching or shrinking all IOIs proportionally, so that RMD remained constant. These modified performances were then paired with unmodified performances having the same global tempo (i.e., the same total duration), and pianist listeners were asked to indicate which performance in each pair was the original one—that is, which

5. The tempi were set by a metronome, which was turned off before the performance began. The medium tempo, however, corresponded to each pianist's spontaneously chosen tempo in an initial performance (see Repp, 1994b, for details of procedure).

sounded more natural. This was a very difficult task, and accuracy was barely above chance level. These results were interpreted as supporting the hypothesis of relational invariance: Changing the tempo while keeping RMD constant did not seem to result in a noticeable deterioration of expressive quality. The present study went two steps further by varying both global tempo *and* RMD orthogonally in *complete* performances of piano pieces.

Experiment 1 was preceded by a very similar experiment that yielded unclear results and therefore will not be reported in detail. It differed from Experiment 1 in that both global tempo and RMD varied over a smaller range, which probably made the stimuli too difficult to discriminate and judge reliably. It also presented the listeners with integral performances rather than with eight-bar excerpts, as described below. Nine pianists participated as listeners, one of them being LPH, whose medium-tempo performance had formed the basis of the experimental materials. The single remarkable result was that LPH was the only listener who showed a striking interaction of global tempo and RMD in her ratings, which fit the pattern of "the faster, the less expressive".[6] LPH was the most experienced pianist among the listeners, but she may also have been specially attuned to her own expressive microstructure. Although not much could be concluded from this intriguing finding, it gave rise to the hope that more consistent results from a group of pianist judges might be obtained when global tempo and RMD were varied over a wider range.

Experiment 1

METHOD

Listeners

Ten pianists participated as listeners. Seven of them were graduate students of piano at the Yale School of Music, one was a graduate student of music theory, one was an undergraduate, and one was a serious amateur (the author).[7]

Materials

Fifteen complete versions of Schumann's "Träumerei" were generated by transforming a single original performance by LPH. That performance was one of three recorded at LPH's preferred ("medium") tempo on a Roland RD-250s digital piano with DP-2 pedal switch (see Repp, 1994a, 1994b, for details). The performance was technically accurate and had

6. Of course, this implies "the slower, the more expressive" which, paradoxically, contradicted her own performance (Fig. 1a).

7. Although the author had had prior experience with the stimuli, he was blind to their order in the test and had no bias in favor of a particular hypothesis. It may be assumed that all listeners were familiar with Schumann's "Träumerei," which is perhaps the most famous piano composition of the Romantic period.

fine artistic expression; despite the slightly synthetic sound ("Piano 1"), it was a pleasure to listen to. The performance data were stored in MIDI format (note onsets and offsets, velocities, and pedal onsets and offsets).

The transformation method involved several steps and decisions. Following Repp's (1992, 1994a) methods of data analysis, eighth-note IOIs were derived from the onsets of the tones with the highest pitch in each cluster of nominally simultaneous tones. IOIs nominally longer than one eighth note were divided into eighth-note IOIs of equal length, to be added up again after transformation. This part was straightforward. The tricky question was how to deal with onset asynchronies, grace notes, note offsets, and pedal information when manipulating tempo and RMD.

Repp (1994a), in his analyses of LPH's and BHR's performances of "Träumerei," has provided some evidence suggesting that onset asynchronies in chords and overlap times (degree of legato) of successive tones do not change systematically with changes in global tempo. However, because it proved technically cumbersome to keep these small intervals constant while transforming the primary IOIs, the MIDI score of LPH's original performance was first edited to eliminate all onset asynchronies and overlaps. Thus, all notes with nominally simultaneous onsets were made to start at the same time as the note from which the IOI was computed, namely, the one with the highest pitch. Similarly, all note offsets in the MIDI score were "regularized" by making them coincide with following note onsets, according to their nominal value in the score. This eliminated overlaps between successive legato notes (the original performance was almost entirely legato) as well as gaps between notes played nonlegato, such as repeated notes of the same pitch.[8] Subsequent listening suggested that the performance did not suffer in expressive quality from these manipulations. As pedaling was almost continuous and created extensive acoustic tone overlaps (see Repp, in press), the elimination of overlaps and gaps in the MIDI score had few audible consequences.

After this regularization, the remaining MIDI events that did not coincide with tone onsets were a few grace notes and the ubiquitous pedal onsets and offsets. According to earlier analyses, grace-note timing in this music was relationally invariant and pedal timing often changed with tempo, although it did not always exhibit relational invariance (Repp, 1994a, in press). It was decided to keep the timing of both these events relationally invariant. That is, after transforming the IOIs, the grace-note onsets and pedal events were moved so that they remained in the same *relative* temporal position within the IOI in which they occurred.

The eighth-note IOIs themselves were transformed by first computing their natural logarithms, then multiplying them by a constant b and adding a constant a, and finally taking the antilogarithm of the result.[9] The values of b (the measure of RMD) were chosen to be 0.6, 0.8, 1.0, 1.2, and 1.4, where a coefficient of less than 1 represents a compression and a coefficient larger than 1 represents an expansion of RMD compared with the original performance (cf. Fig. 1). Starting with the original medium-tempo performance ($a = 0$, $b = 1$), two values of the intercept a were chosen to generate slower and faster versions whose tempo still seemed aesthetically acceptable. The total durations of the resulting fast, medium, and slow performances differed by increments of 25%. A different b coefficient was then applied to the medium-tempo performance, and an accompanying value of a was found by trial and error, so as to keep the total duration constant. The a coefficients for the re-

8. These overlaps and gaps are defined with respect to the note onsets and offsets in the MIDI score. *Acoustic* and *perceptual* overlaps and gaps are a different matter that need not be considered here (see Repp, 1995). Despite the elimination of gaps in the MIDI score, the onset of a repeated tone remained clearly perceptible, because of the acoustic decay of the preceding tone before its nominal offset.

9. This is equivalent to applying the power function $y = e^a x^b$, also suggested by Desain and Honing (1992). Natural logarithms were used here for a trivial technical reason; note that the performance data (Figure 1) are displayed in terms of base 10 logarithms.

TABLE 1
Additive (*a*) Coefficients Used in Experiment 1

Tempo	*b* Coefficient 0.6	0.8	1.0	1.2	1.4	Duration (s)
Fast	2.319	1.046	–0.227	–1.504	–2.781	115.0
Medium	2.546	1.273	0.000	–1.277	–2.554	144.3
Slow	2.767	1.494	0.221	–1.056	–2.333	180.0

NOTE. These are the intercepts of the linear functions relating the original and transformed ln(IOI) values, with the *b* coefficients being their slopes.

maining versions could then be determined arithmetically, as they were a simple linear function of the *b* coefficients. All these coefficients are shown in Table 1.

All data manipulations were carried out in a spreadsheet/graphics program (DeltaGraph Professional) into which the original MIDI data had been imported as text files. After transformation, the IOIs were cumulated back into absolute onset times, and the data were reconverted into MIDI files for audio output via the Roland RD-250s digital piano. To get multiple ratings of each version, the 24-bar piece was divided into three 8-bar sections (excerpts) that were presented and evaluated separately.[10]

Procedure

The 45 eight-bar sections were recorded onto DAT tape, together with the complete original regularized medium-tempo performance, which served as familiarization. All listeners were tested individually in a quiet room and heard the music over Sennheiser HD540II earphones. The DAT recorder was programmed to deliver the excerpts in a different order to each listener.

Each listener first heard the complete performance. (S)he was asked to consider it approximately 7 or 8 on a 10-point scale (1 = poor, 10 = excellent) and to judge the quality of the following performances relative to it, as well as relative to any other preceding versions of the same tempo.[11] The test excerpts were presented in three groups of 15, corresponding to the 3 eight-bar sections of the piece, which were presented in the same natural order to all subjects (i.e., first bars 1–8, then bars 9–16, and finally bars 17–24). Each group was di-

10. Actually, each complete performance consisted of 32 measures, as bars 1–8 were repeated. This repetition was not used in the experiment. The duration of an eight-bar excerpt at any tempo thus was roughly one fourth, not one third, of the total duration given in Table 1. Each excerpt started with an upbeat, and some slight adjustments were made in the MIDI scores to achieve smooth beginnings and endings of each excerpt when presented separately.

11. As an artificial transformation can hardly improve a fine artistic performance, it seemed highly likely that the original would be rated higher than any other version when it recurred as a test stimulus. Therefore, it seemed appropriate to anchor the rating scale initially by asking listeners to assign a relatively high rating to the original performance, which made it likely that similarly high ratings would be assigned to its eight-bar sections when they recurred during the test, so that most of the steps of the rating scale were available for evaluation of the transformations. Also, to observe a shift of the peak rating as a function of global tempo, it was desirable that there be a clear central peak (i.e., at $b = 1$) in the ratings of the five medium-tempo versions.

vided into three blocks of five versions each, with the global tempo being constant within each block. The order of blocks (global tempi) within groups and the order of excerpts (RMD values) within each block were variable and approximately counterbalanced across listeners. Each individual listener, however, received the same order of global tempi within each group, and the same order of RMD values within tempi in any given group (but different orders in different groups), in order to equate any sequential context effects across tempi.

The listeners were asked to assign a rating at the end of each performance excerpt. They were asked to try to use the whole range of the scale and to avoid giving the same rating to two excerpts in the same block; decimals and ratings outside the 10-point range were permitted (but rarely used). It was emphasized that discrimination among the excerpts within a block was much more important than the relative ratings of the performances according to tempo (i.e., between blocks). The listeners were thus asked specifically to focus on the RMD dimension and to indicate their relative preference among excerpts having the same global tempo. Each group of 15 excerpts was followed by a short break.

RESULTS AND DISCUSSION

The average ratings of the 10 judges are shown in Figure 2 as a function of RMD (i.e.,the b coefficient), separately for the three global tempi. As expected, at the medium tempo the highest rating was given to the original (regularized) performance ($b = 1$). At the fast tempo, however, the highest rating was given to the performance with $b = 0.8$, whereas at the slow tempo it was given to the performance with $b = 1.2$. The tempo by RMD interaction was significant in a repeated-measures ANOVA [$F(8,72) = 3.41$, $p < .003$]. In addition, there was a significant main effect of RMD [$F(4,36) = 4.81$, $p < .004$]. The apparent preference for the medium tempo over the other tempi was not reliable because of large individual variability, and

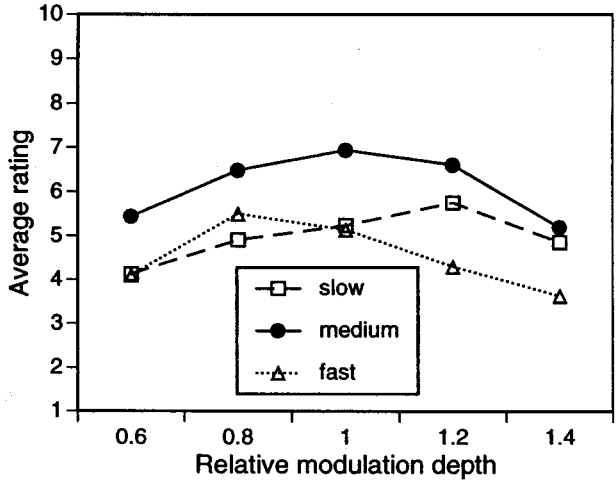

Fig. 2. Average ratings by 10 subjects of 15 performances of Schumann's "Träumerei" varying in global tempo and in relative modulation depth (RMD).

there were no differences or interactions due to the three eight-bar sections of the piece. Pairwise comparisons of tempi suggested that the interaction with RMD was reliable for slow versus fast [$F(4,36) = 4.09$, $p < .008$] and for slow versus medium tempo [$F(4,36) = 3.33$, $p < .03$], but not quite for medium versus fast tempo [$F(4,36) = 2.32$, $p < .08$].

These results support the hypothesis of "the faster, the less expressive": Listeners exhibited a preference for a reduced RMD at a fast tempo and for an enhanced RMD at a slow tempo. The effect is small, however. It was possible to assess the reliability of each individual subject's results by considering the 3 eight-bar excerpts as a random factor crossed with the fixed factors of RMD and tempo. In these individual repeated-measures ANOVAs, 8 of 10 listeners showed significant ($p < .05$) main effects of RMD and 9 showed significant main effects of tempo, which suggests that they could discriminate among the different performances. However, only 3 subjects showed a significant RMD by tempo interaction. Of course, these individual ANOVAs had less statistical power than the overall analysis, but they demonstrate the relative fragility of the crucial interaction.

Experiment 2 represents an attempt to replicate this interaction with a different piece of music.

Experiment 2

SOME PERFORMANCE DATA

The music in this study was "La fille aux cheveux de lin," from Book I of Debussy's preludes. The complete prelude was performed seven times by a talented young pianist, a second-year graduate student at the Yale School of Music. The first three times, she played it at her preferred tempo, alternating with three other pieces that were recorded in the same session. At the end of the session, she was asked to play the Debussy piece twice each at the slowest and fastest tempi that she found aesthetically acceptable. The instrument was a Yamaha MX100A Disclavier (an upright acoustic piano with added electronic components, connected to a microcomputer) located at the Yale Center for Studies in Music Technology. The performances were recorded in MIDI format.

The "primary" note onsets (i.e., of the note with the highest pitch in each cluster) were identified in the MIDI scores, and IOIs were calculated. The IOIs were then averaged across the two or three performances with the same nominal tempo, to reduce random variability. In contrast to Schumann's "Träumerei," which contains mainly eighth-note IOIs, the Debussy piece contains a variety of nominal IOI durations: sixteenth notes, eighth notes, and longer notes. To eliminate the contribution of nominal

differences in IOI duration and leave only expressive timing variation, all IOIs were "normalized" to sixteenth-note units by dividing longer IOIs by the number of sixteenth-note units they contained. The scatter plot of log(IOI) values comparing the different tempi is shown in Figure 3a. The

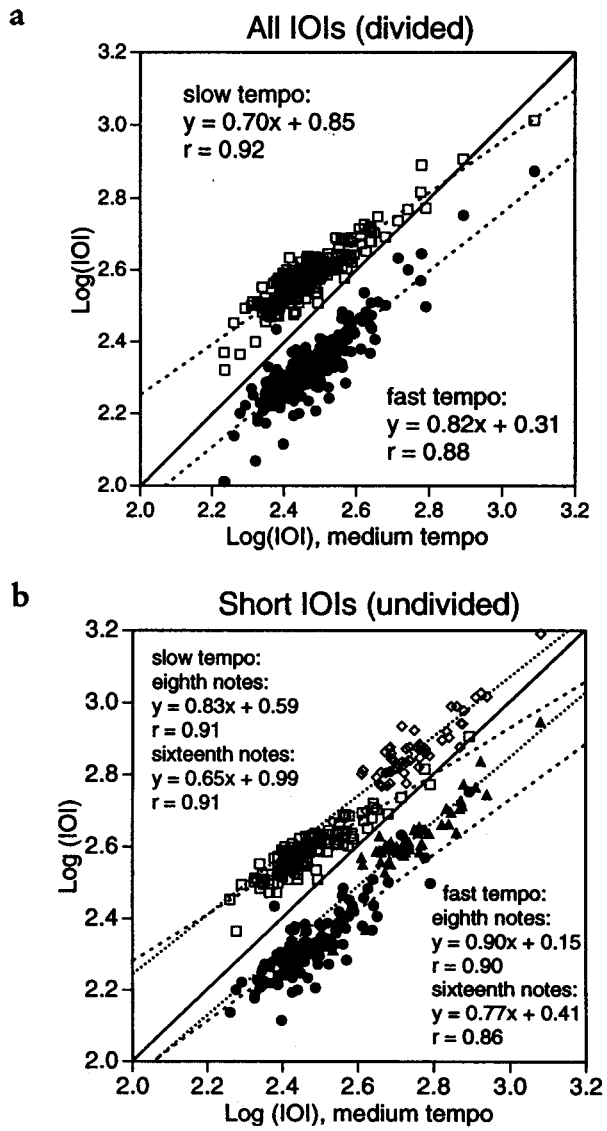

Fig. 3. Relationships between logarithms of interonset intervals (IOIs) at a medium tempo and at a fast and slow tempo, respectively, in performances of Debussy's "La fille aux cheveux de lin" by one pianist. (a) All IOIs divided into sixteenth-note units. (b) Sixteenth notes (circles and squares, dashed regression lines) and undivided eighth notes (triangles and diamonds, dotted regression lines).

deviation of the slopes of the regression lines from unity was even more striking here than in Figure 1, although there was also greater variability.[12] However, the slopes of the regression lines were clearly smaller than the correlations, indicating again a reduction in RMD at both fast and slow tempi.

Figure 3b shows a comparison of the most prevalent short IOIs, those of sixteenth and (here not normalized) eighth notes. Although both types of IOIs had regression lines with slopes of less than 1, sixteenth notes had especially shallow slopes.[13] The slopes were smaller than the correlations in all but one case (eighth notes at the fast tempo). It seems that the reduction in RMD was most pronounced for the shortest notes in the music.

These observations confirm the trends found in the "Träumerei" performances. Again, it seems that the pianist played more expressively at her preferred tempo than at either a faster or a slower tempo. The more complex inventory of IOIs raised the question, however, how the RMD transformation in the perceptual test materials should be handled: Should it be carried out on the original undivided IOIs or on the IOIs divided into sixteenth notes? Should sixteenth notes be treated differently from the others? It was decided, somewhat arbitrarily, to use the same method as in Experiment 1, namely, to divide all IOIs into sixteenth-note units before transformation and then to add up the transformed fractions to reconstitute the longer IOIs.

METHOD

Listeners

Nine pianists participated as listeners. They included four graduate students of piano at the Yale School of Music (one of whom had provided the performances just described), three excellent undergraduate pianists (all had performed as soloists with the Yale Symphony Orchestra the same season), one semiprofessional accompanist, and one amateur (the author). All indicated that they knew the music well.

Materials

One of the original medium-tempo performances was selected as the basis for the experimental manipulations. This performance and all its descendants were reproduced on the Roland RD-250s digital piano used in Experiment 1, which sounded very acceptable and avoided problems connected with acoustic recording.[14] As in Experiment 1, the performance was then "regularized" by synchronizing all note onsets and offsets according to

12. The "difference correlations" (–0.70 and –0.39 for medium vs. slow and medium vs. fast tempo, respectively) were highly significant.

13. All difference correlations were significant, reaching a remarkable –0.77 for sixteenth notes at the slow tempo.

14. The only necessary modification was elimination of the soft pedal, which caused unpleasantly abrupt changes in dynamics on the Roland. An apparent misreading by the pianist of three eighth notes as sixteenth notes was also corrected at this stage.

TABLE 2
Additive (a) Coefficients Used in Experiment 2

	b Coefficient					
Tempo	0.6	0.8	1.0	1.2	1.4	Duration (s)
Fast	1.931	0.784	−0.365	−1.518	−2.675	93.8
Medium	2.297	1.150	0.000	−1.153	−2.310	135.1
Slow	2.505	1.358	0.209	−0.944	−2.101	166.4

NOTE. These are the intercepts of the linear functions relating the original and transformed ln(IOI) values, with the b coefficients being their slopes.

their notated values. In each cluster of nominally simultaneous events, the onset of the note with the highest pitch again served as the reference. Regularization did not seem to affect performance quality. Note events that were left in their original relative temporal positions within IOIs included two arpeggiated chords (bars 12 and 35), three "split" left-hand chords (bars 6, 16, and 30), and two broken octaves at the end of the piece (bars 36 and 37). Pedal onsets and offsets also remained in their original relative positions. The damper pedal was used extensively throughout the music.

Transformation of the IOIs was carried out according to the same design and regime as in Experiment 1. All IOIs were divided into sixteenth-note intervals before transformation. The a and b coefficients and the overall durations of the performances are shown in Table 2. The slow and fast tempi were those chosen by the pianist herself in her slow and fast performances. Although the 23% increase in duration from medium to slow tempo was comparable to that in Experiment 1, there was a larger (44%) increase here from fast to medium tempo.

Procedure

The procedure was the same as in Experiment 1, except that the performances were presented in integral form, so that each was judged only once by each subject. The original medium-tempo performance again served as familiarization, and subjects were asked to assign it a "9" on the 10-point rating scale. It was followed by three blocks of five performances each. The order of blocks (global tempi) and of performances (RMD values) within blocks was varied across subjects, but the same order of RMD values was used in the three blocks for any given subject (except for the first two subjects, who received different orders in the three blocks).

RESULTS AND DISCUSSION

The average ratings are shown in Figure 4. As expected (and instructed), subjects gave a high rating to the original medium-tempo performance, but they liked the performance with slightly exaggerated timing variation (b = 1.2) just as much, and even the most exaggerated performance (b = 1.4) received a rather high rating.[15] Performances with reduced timing variation

15. Unlike pianist LPH, who seemed exceptionally sensitive to modifications of her own timing microstructure in the earlier version of Experiment 1, the pianist who had provided the original performance for this experiment did not give ratings that were radically different from those of the other subjects.

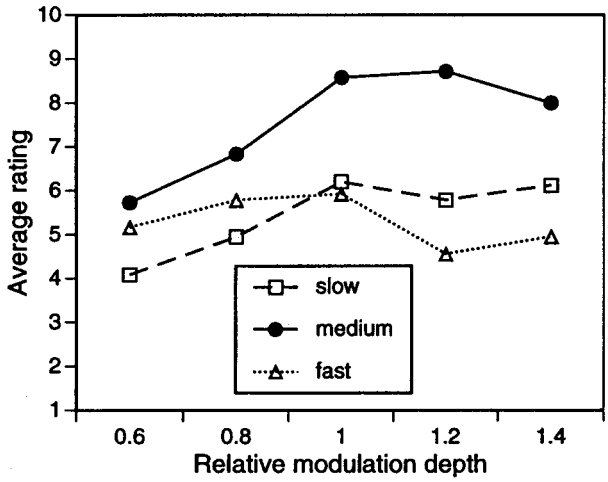

Fig. 4. Average ratings by nine subjects of 15 performances of Debussy's "La fille aux cheveux de lin" varying in global tempo and in relative modulation depth.

(b = 0.8, 0.6) were liked much less. The slow performances present a rather similar picture, although with lower ratings overall. At the fast tempo, however, this asymmetry was absent, and understated performances were actually rated slightly higher than exaggerated ones. This pattern of results again represents a significant RMD by tempo interaction [$F(8,64) = 3.23, p < .004$]. In addition, there were significant main effects of tempo [$F(2,16) = 10.29, p < .002$] and of RMD [$F(4,32) = 6.30, p < .0008$]. Pairwise comparisons of tempi showed the interaction to be highly significant for medium versus fast tempo [$F(4,32) = 6.52, p < .0007$], marginally significant for slow versus fast tempo [$F(4,32) = 2.97, p < .04$], and nonsignificant for medium versus slow tempo [$F(4,32) = 0.69$].[16]

The results for medium versus fast tempo, and especially for slow versus fast tempo, are in agreement with those of Experiment 1 and thus support the hypothesis of "the faster, the less expressive." The comparison of slow and medium tempo, however, tends in the opposite direction. A significant effect in this comparison might have given support to the "optimal tempo" hypothesis, but the nonsignificant trend does not warrant any conclusions. The fact that the tempo difference between slow and medium was smaller in this experiment than that between medium and fast may have been partially responsible for the result. Thus, on the whole, the results of Experiment 2 are consistent with those of Experiment 1, especially if only the

16. Because individual subjects gave only a single rating of each performance, individual results could not be analyzed statistically and were somewhat variable. There was every reason to believe, however, that the listeners were able to discriminate among the different versions.

extreme tempi are considered. Again, however, the interaction represents a relatively small effect.

General Discussion

The present results suggest, tentatively, that expressive timing microstructure is not completely independent of global tempo, even when the tempo variations do not affect rhythmic organization (i.e., do not lead to interpretable qualitative changes in the timing profile). Although the timing profiles of performances played at different tempi may be highly similar (Repp, 1994a), they do exhibit statistically reliable differences (see also Desain & Honing, 1994). Correspondingly, listeners seem to expect the timing pattern to change with global tempo. This change, as long as the tempo stays within aesthetically acceptable limits, seems to be quantitative rather than qualitative in nature: It takes place along the continuum of RMD or degree of expressiveness.

There is a discrepancy, however, between the (admittedly limited) production and perception data presented here. The perceptual judgments suggest that listeners expect the RMD to be reduced at a fast tempo, and this is in agreement with the performance measurements. At a slow tempo, however, listeners seem to expect the RMD to be increased (Exp. 1) or unchanged (Exp. 2), whereas pianists appear to reduce the RMD when playing at a slow tempo. However, as already pointed out, this reduction may be due to the exigencies of playing at an unfamiliar tempo: The pianist may have to devote attention to keeping the tempo, at the expense of expression. Perhaps this effect would disappear if a pianist practiced a piece at a slow tempo. Although tempo preferences may also affect perceptual evaluation, the perceptual data came from a larger sample of pianists whose tempo preferences presumably were both diverse and less pronounced (unless a pianist had studied the piece recently). Therefore, the perceptual data may be more representative than the performance data.

The present results must be considered preliminary for a number of reasons. First, they derive from only two compositions, both relatively slow and lyrical in character; it remains to be seen whether the results generalize to other pieces. Second, the transformations were applied to only one specific performance of each piece, which may also limit the generality of the findings. Third, the RMD transformation procedure involved certain decisions that future research may call into question. While the elimination of tone onset asynchronies and overlaps is relatively uncontroversial and did not seem to harm performance quality, partly because of extensive pedal use, the treatment of longer IOIs, arpeggios, and grace notes is more critical. There is good evidence from earlier studies (Repp, 1994a, in press) that

the timing of the relatively slow grace notes in "Träumerei" remains relationally invariant with changes in global tempo; however, faster grace notes may behave differently (see Desain & Honing, 1992, 1994). The timing of the arpeggios in the Debussy piece was allowed to vary proportionally with global tempo, although this was perhaps not the optimal procedure. Most importantly, the treatment of nominally long IOIs in terms of equal subunits is in need of a firmer empirical and theoretical basis.

The present study explored a new methodology that endeavors to stay as close as possible to genuine artistic performance and aesthetically informed listening. There have been few if any previous studies in which integral performances have been subjected to computer-controlled transformation that preserved their human quality and general aesthetic acceptability. Power-function transformations of expressive timing and the concept of RMD seem to have ecological validity in that they appear to preserve important characteristics of artistic time management while moving along a continuum from understatement to exaggeration. Desain and Honing's (1992) calculus for expressive transformations incorporates a very similar procedure. Whereas the present approach was motivated by empirical observations, theirs was based mainly on theoretical considerations or common sense. However, their system, which makes possible much more sophisticated, structure-sensitive transformations, has not been used in formal experiments so far. The power-function transformation also seems intuitively compatible with Repp's (1992) finding of parabolic timing functions and Todd's (1992, 1995) recent model of expressive timing, which represents tempo modulations as linear changes in the velocity of musical motion over time. The MIDI-based manipulation of human performances seems a promising technique for certain purposes, as long as music performance synthesis is not sufficiently developed to produce truly humanlike outcomes.

A final issue that needs to be commented on relates back to the introductory paragraph on transformational invariance. The invariance of a melody across changes in pitch register can be demonstrated by (1) asking musicians to play the same melody in a different key and measuring the resulting pitch relationships and (2) by asking listeners to identify the transposed melody as being the same as the original. The same method may be applied to a rhythmic pattern played at different tempi. When it comes to expressive microstructure, however, we are dealing with a subtle, complex, and subcategorical form of variation whose invariance across transformations is difficult to judge directly, especially when quantitative rather than qualitative differences are at stake. That is, if a musician were asked to play a piece with exactly the same degree of expressive timing but at a different tempo, (s)he would either deny that this is possible or go ahead but not really know whether (s)he is following the instructions. What a musician

can do is play the same music at a different tempo with the expression that seems best at that tempo, and this is what the pianists in the present study did. Similarly, even highly experienced listeners would find it extremely difficult to judge whether two performances differing in global tempo have exactly the same degree of tempo modulation.[17] What these listeners can do is judge the expressive quality of performances varying in tempo, and this is what the present listeners were asked to do. The interdependence of tempo and RMD demonstrated here thus resides in the domain of artistic performance and aesthetic evaluation, not in that of psychophysical judgment. Therefore, the present results do *not* demonstrate that the intended or judged degree of expressive timing variation depends on tempo, but rather that the aesthetically most satisfying RMD shows such a dependency.[18]

References

Clarke, E. F. (1982). Timing in the performance of Erik Satie's 'Vexations.' *Acta Psychologica, 50,* 1–19.

Desain, P., & Honing, H. (1992). Towards a calculus for expressive timing in music. In P. Desain & H. Honing, *Music, mind and machine* (pp. 175–214). Amsterdam: Thesis Publishers.

Desain, P., & Honing, H. (1994). Does expressive timing in music performance scale proportionally with tempo? *Psychological Research, 56,* 285–292.

Gabrielsson, A. (1987). Once again: The theme from Mozart's Piano Sonata in A major (K. 331). In A. Gabrielsson (Ed.), *Action and perception in rhythm and music* (pp. 81–103). Stockholm: Royal Swedish Academy of Music (Publication No. 55).

Gentner, D. R. (1987). Timing of skilled motor performance: Tests of the proportional duration model. *Psychological Review, 94,* 255–276.

Handel, S. (1992). The differentiation of rhythmic structure. *Perception & Psychophysics, 52,* 497–507.

Handel, S. (1993). The effect of tempo and tone duration on rhythm discrimination. *Perception & Psychophysics, 54,* 370–382.

Handel, S., & Lawson, G. R. (1983). The contextual nature of rhythmic interpretation. *Perception & Psychophysics, 34,* 103–120.

Heuer, H. (1991). Invariant relative timing in motor-program theory. In J. Fagard & P. H. Wolff (Eds.), *The development of timing control and temporal organization in coordinated action* (pp. 37–68). Amsterdam: Elsevier.

17. In informal pilot work, the author has explored this issue with very short musical excerpts. It seems that, in judging the relative similarity of timing patterns across changes in tempo, a listener would not only be biased by the tempo difference as such but also would rely merely on local features (especially the initial and final IOIs) in making the judgment. (See also Handel, 1993.)

18. This research was supported by National Institutes of Health grant MH-51230. I am grateful to Charles Nichols and Linda Popovic for extensive assistance, to Jonathan Berger (director, Yale Center of Studies in Music Technology) for allowing me to use his facilities, to the participating pianists for their patience, and to Jamshed Bharucha, Stephen Handel, Henkjan Honing, Caroline Palmer, and Burt Rosner for helpful comments on an earlier draft.

Hulse, S. H., Takeuchi, A. H., & Braaten, R. F. (1992). Perceptual invariances in the comparative psychology of music. *Music Perception, 10,* 151–184.

Michon, J. A. (1974). Programs and "programs" for sequential patterns in motor behaviour. *Brain Research, 71,* 413–424.

Monahan, C. B., & Hirsh, I. J. (1990). Studies in auditory timing: 2. Rhythm patterns. *Perception & Psychophysics, 47,* 227–242.

Palmer, C. (1989). Mapping musical thought to musical performance. *Journal of Experimental Psychology: Human Perception & Performance, 15,* 331–346.

Parncutt, R. (1994). A perceptual model of pulse salience and metrical accent in musical rhythms. *Music Perception, 11,* 409–464.

Perkell, J. S., & Klatt, D. H. (Eds.) (1986). *Invariance and variability in speech processes.* Hillsdale, NJ: Erlbaum.

Repp, B. H. (1992). Diversity and commonality in music performance: An analysis of timing microstructure in Schumann's "Träumerei." *Journal of the Acoustical Society of America, 92,* 2546–2568.

Repp, B. H. (1994a). Relational invariance of expressive microstructure across global tempo changes in music performance: An exploratory study. *Psychological Research, 56,* 269–284.

Repp, B. H. (1994b). On determining the basic tempo of an expressive music performance. *Psychology of Music, 22,* 157–167.

Repp, B. H. (1995). Acoustics, perception, and production of legato articulation on the piano. *Journal of the Acoustical Society of America, 97,* 3862–3874 .

Repp, B. H. (in press). Pedal timing and tempo in expressive piano performance: A preliminary investigation. *Psychology of Music.*

Schmidt, R. A. (1975). A schema theory of discrete motor skill learning. *Psychological Review, 82,* 225–260.

Sorkin, R. D., & Montgomery, D. A. (1991). Effect of time compression and expansion on the discrimination of tonal patterns. *Journal of the Acoustical Society of America, 90,* 846–857.

Todd, N. P. McA. (1992). The dynamics of dynamics: A model of musical expression. *Journal of the Acoustical Society of America, 91,* 3540–3550.

Todd, N. P. McA. (1995). The kinematics of musical expression. *Journal of the Acoustical Society of America, 97,* 1940–1949.

Viviani, P., & Laissard, G. (1991). Timing control in motor sequences. In J. Fagard & P. H. Wolff (Eds.), *The development of timing control and temporal organization in coordinated action* (pp. 1–36). Amsterdam: Elsevier.

Warren, W. H. Jr., & Shaw, R. E. (Eds.) (1985). *Persistence and change. Proceedings of the First International Conference on Event Perception.* Hillsdale, NJ: Erlbaum.