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Does expressive timing in music performance scale proportionally with tempo?

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Summary. Evidence is presented that expressive timing in music is not relationally invariant with global tempo. Our results stem from an analysis of repeated performances of Beethoven's variations on a Paisiello theme. Recordings were made of two pianists playing the pieces at three tempi. In contrast with the relational-invariance hypothesis (see Repp, 1994), between-tempo correlations were in general lower than within-tempo correlations. Analyses of variance of log-transformed inter-onset intervals (IOIs) showed significant interactions between tempo and IOI, i.e., evidence against a proportional relation between timing and tempo. Complex, but consistent, nonproportional patterns were shown in the analyses of the timing of the grace notes in the piece. The analysis suggests that timing aspects of music are closely linked to the musical structure and can be studied and manipulated only respecting this relation – not as a global timing pattern or tempo curve. Finally, it is shown that methodological issues of data collection and analysis had a significant influence on the results.

Introduction

In Desain and Honing (1992; 1993) we criticized the use of tempo profiles as a representation of timing in music performance independent of the musical structure – in both cognitive modeling and technical applications. In these so-called "tempo curves," measurements of local performance tempo, or of note inter-onset time (IOI), are presented against score time. We studied two quite different, but related, pieces of music that share a harmonic, melodic, and metrical structure (a theme and a variation). Many transformations – scaling the measured tempo curve in global tempo, applying a tempo curve from the theme to the variation, or even simply changing the key from major to minor without modifying the tempo curve – produced results judged unmusical, and we argued against their use on this basis. Instead, we suggested that the timing aspects of music are linked to its structural aspects and should therefore be studied and manipulated respecting this relation and as a global transformation based on a tempo curve.

Repp (1994), prompted by our work, explored the scaling of expressive aspects of music systematically with regard to global tempo, for performances of Schumann's "Träumerei." In his work, which will be referred to as the "Träumerei" study, there was relational invariance: expressive timing scaled "approximately" proportionally with tempo. Consequently, a tempo curve for a different tempo can be obtained if the original is plotted on a log-duration y axis and shifted vertically.

To gain further understanding on this issue, we present a new analysis. We follow the lines as set out in the "Träumerei" study to allow easy comparison. However, we shall restrict ourselves to the examination of the patterns of onset timing.

Method

The music. For our study, we used the theme and first variation from the six variations (WoO 70) on the theme "Nel cor più non mi sento" by Giovanni Paisiello, composed by Ludwig van Beethoven in 1795 (see Figure 1). These variations belong to the species of melodic variation: they all retain the complete melody (Brendel, 1991). The theme and first variation were chosen because of their simplicity and their similar metrical, harmonic, and melodic structure (hereafter we refer to them as Theme and Variation). Both the Theme and the Variation are 20 bars in length. The Theme consists of an 8-bar phrase (*Stollen*), followed by a 6-bar phrase (*Stollen*), and finishes with a 6-bar phrase (*Abgesang*).

The first phrase consists of two subphrases that, in turn, can be divided into two further subphrases. The next phrase consists of three subphrases, and the final phrase could be divided in two subphrases, of which the first could be divided into two again, but other analyses are possible. The topmost level of the phrase-structure tree of the Variation follows the phrase structure of the Theme. The Theme has a typical

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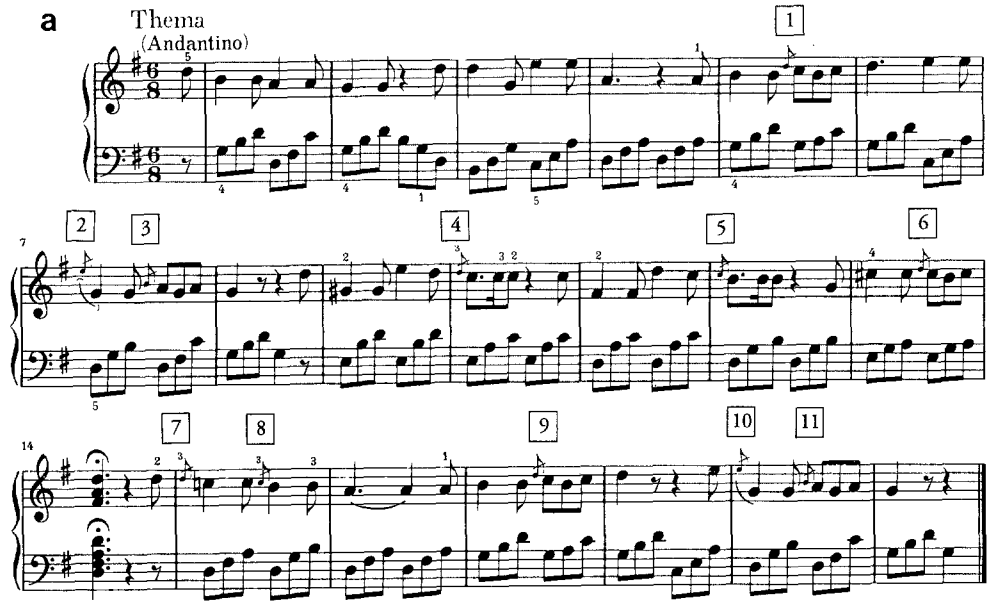

Fig. 1a. The score of the Theme: reproduced from Beethoven, *Variationen für Klavier, Vol. I.* Munich: G. Henle Verlag (with kind permission from the publisher)

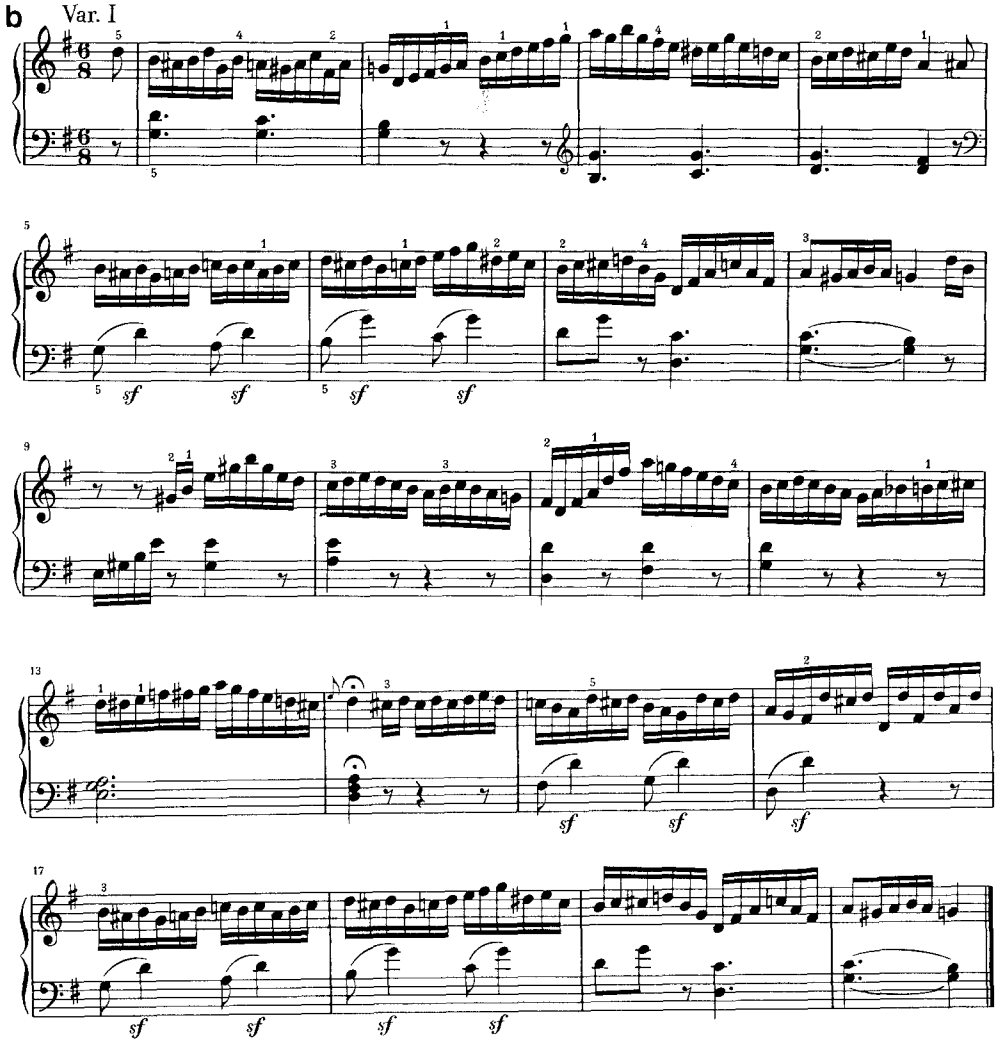

Fig. 1b. The score of the Variation: reproduced from Beethoven, *Variationen für Klavier, Vol. I.* Munich: G. Henle Verlag (with kind permission from the publisher)

Alberti Bass (broken-chord) accompaniment, whereas the Variation has predominantly a chord accompaniment. The Theme has a varied rhythmical structure and several ornaments, whereas the Variation is chracterized by runs of sixteenth notes.

Performers. The two performers were BH, a professionally trained pianist in his early sixties, and RB, a professional pianist in his early thirties. Both were familiar with the Beethoven's "Theme and Variation." BH had recently studied and performed all six variations.

Recording procedure. Our recording procedure, described in Desain and Honing (1992), was almost identical to that used in the "Träumerei" study. An important difference was the use of a synthesized harpsichord instead of an electronic piano. The harpsichord compelled the subjects to use timing as their only means of expression, and thereby finesses the difficult problem of the interaction of time and dynamic parameters (e.g., Drake & Palmer, 1993). To make our observations comparable to the "Träumerei" study, we collected new data, using an instrument and a recording procedure similar to those used in the "Träumerei" study.

The instrument was a Roland D-5 synthesizer (with only its keyboard and MIDI output being used), without sustain pedal, connected to an Apple Macintosh Quadra 700 computer running the EZ Vision sequencer software (time resolution 1 ms, within the limits of MIDI transmission speed) under System 7 (with no other programs running). The (MIDI Thru) output of the computer/sequencer was connected to a Yamaha TG-100 sound generator set to a piano sound (1 GrandPno), without reverb, played over a SONY SRS-D4 loud speaker system.

Both pianists were recorded in separate sessions. After some practice on the instrument, the pianist played the full piece at his preferred tempo. Subsequently, each pianist performed the piece at a slower, and at a faster, tempo. The tempi were chosen by the performers to form the end points of a musically sensible range of tempi. By contrast, in the "Träumerei" study they were set by the experimenter. The tempi are given in Table 1. The instruction was to play naturally, as musically as possible. No metronome was used. Both performers took a short time getting used to the instrument.

Both performers played the Theme and the Variation at each of the three tempi until they had recorded four performances that they judged to be acceptable (this took an average of five recordings per tempo and piece). The piece was recorded first at the normal or medium tempo, followed by the series in a slow and a fast tempo. After a break, the acceptable performances were played back to the performer, who was asked to select the three best performances of both pieces at each of the three tempi.

The recorded data were stored in standard MIDI files (IMA, 1983). The data files were imported into POCO, a computer environment for research on expression in music (Honing, 1990). For both pieces, a score was created from one performance (partly by quantization and partly by hand editing). It was annotated by means of POCO tools, with structural information, including metric and phrase structure, chords and ornaments, the voices, and the left- and right-hand parts. The structural information in the score was transferred to each performance with the POCO performance-score-matching facility. The matching facility eliminates any further hand annotation of individual performances (a tedious process) and enables an easy analysis of information at different structural levels, filtering out certain musical objects or voices, and so on. This process is also a secure check against errors in the performance. The resulting data were imported into a statistical data-analysis program (StatView II) for further processing.

Issues in measuring timing

A number of methodological issues arise in the study of expressive timing, and, as we shall show, methodology has a significant influence on the reults. The issues described below apply to all studies that use a global-timing pattern or profile.[1]

Selecting onsets in polyphonic music

What note onsets should be used in calculating the intervals between notes (the IOIs) in a performance? Parallel structures (e.g., notes notated as a chord in the score) and ornamental structures (e.g., grace notes) present a difficulty. For parallel onsets, the basic options are to use the onsets of the top voice (the highest in pitch), the onsets of melody derived from music-theoretical analysis, or the note whose onset happens to be first (see Figure 2). There is no optimal solution (apart from restricting oneself to the study of monophonic music). Repp (personal communication) suggests that the differences in measurement can be neglected, and it is not clear which method was used in the "Träumerei" study. Because the melodic voice may in fact carry the perceptual tempo, we use the melody-only approach.

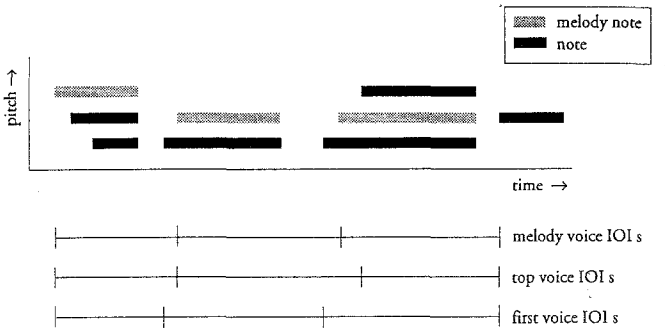

Fig. 2. The treatment of parallel structures

Removing grace notes

For a grace note, no tempo measurement can be calculated, since no reference-note duration is given in the score. So ornamental notes have to be studied separately (as e.g., in Repp, 1994). But the perceptual effect of a short grace note on the perceived timing of the following note can be quite considerable. This can be verified easily by listening to a performance from which the grace notes have been artificially removed. The strange-sounding effect seems to parallel the time-shrinking phenomenon described by Nakajima, ten Hoopen, and van der Wilk (1991). Perceptual time-shrinking was discovered by the use of short time intervals in the range commonly found in musical ornaments. In our case there are so many grace notes in the Theme (in contrast to Schumann's "Träumerei", which has only two proper grace notes), that one has to guard against letting perceptual effects invalidate the analysis.

To stay on the safe side, the onset of the note before a grace note and the onset of note following the grace note

[1] In the "Träumerei" study, the following method was used to preprocess the timing data. Of all the note onsets, the onsets of grace notes were removed because their timing cannot be related to a notated score duration – no tempo can be calculated. The onsets of notes that form part of a chord were also removed, except for the one note (it is unclear whether this is the highest note or the melody note). Then the IOIs were calculated by taking the difference of two subsequent onsets. The IOIs are related to their duration in the score by dividing the IOI of a longer note into several equal intervals (i.e., having multiple data points for IOIs longer than one eighth note; see Fig. 2 in Repp, 1994). The procedure transforms the data to a 1/tempo measurement based on a regular time grid in the score. These data are transformed to a log scale. The data are still referred to as an *IOI profile*, but *log-beat duration profile* would be a better term

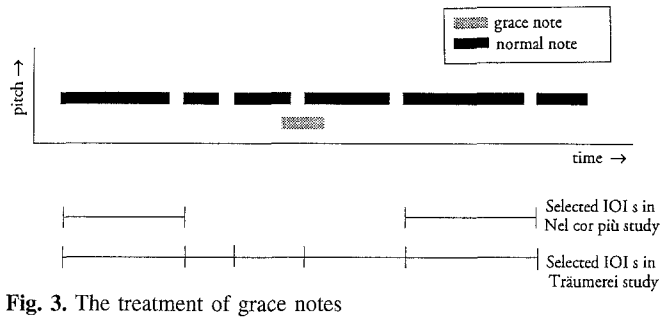

Fig. 3. The treatment of grace notes

were removed (see Figure 3). This reduced the data set of the Theme by 33 data points and the Variation by 3 data points. The removal of this much local detail biasses the analyses towards global-rate or tempo aspects. Because the local structure of grace notes is one example that, as we will show, does not generally scale proportionally with tempo, the exclusion of this source of nonproportionality strengthens our case against relational invariance.

Normalized IOIs vs. sampled IOIs

A third issue concerns the sampling of the IOIs on a time grid. In the way it is used in the "Träumerei" study, sampling duplicates data points for the tempo measurements of longer notes. Notes with a long nominal (score) duration may exert undue influence on the resultings correlation.[2] This method appears to be based on the notion of a continuous (mental) representation of tempo, a representation that can be accessed, for example, by sampling at regular intervals, even when there are no events – a simplification quite rightly criticized in Gibson (1975). We have therefore restricted the analysis to IOIs normalized by score duration.

Magnitude scale of time duration

A simple duration scale (consisting of raw IOIs) cannot be used in general to calculate correlations between timing profiles, because different note durations in the score would swamp any timing effects. A beat-duration scale, the inverse of a tempo scale, does not suffer from that difficulty. A choice seems quite arbitrary, but we can fold back Repp's conclusion (timing is relational invariant with respect to global tempo) to a microlevel. Accordingly, timing should be measured on a logarithmic scale. And this makes the difference between duration and tempo (1/duration) measurement essentially irrelevant. Moreover, consistency in performances measured by correlation of log duration or log tempo would theoretically coincide better with perceived similarity of timing patterns.[3]

[2] The correlation measures become higher when the sampling method (with a maximum increase of .09 and an average of .02 compared to nonsampled data) is used – which would bias the results in our study toward relational invariance. Repp (1994; fn 4) argued that the effect of duplicated data points is negligible for the correlations, but he removed these data points for the ANOVA.

Averaging across Performances

Apart from making comparisons of between- and within-tempo correlations impossible, averaging within-tempo IOIs across performances seems to ignore the possibility that higher-order control of timing of subsequent events may have a systematic effect on the data. If a log-magnitude scale for IOIs is most suitable, combining the data before the log transformation is inappropriate.[4] We therefore report only average correlations of individual performances.

Results and Discussion

Timing patterns at the medium tempo

Figures 4a and 4b show a section of the timing patterns for the three repeated performances in a medium tempo for each pianist of both the Theme and the Variation.

In Figures 4a and 4b, a high peak represents a long beat duration. These occurred consistently at specific structural boundaries (e.g., in Figure 4a at the end of bar 8). BH employed a deeper rubato (larger tempo excursions) than RB.

The correlations between the overall profiles of the three performances at the same tempo can be used to measure the consistency and reliability of the data. The average overall correlation between the three individual performances at the medium tempo is for RB .77 (Theme) and .80 (Variation) and for BH .81 (Theme) and .95 (Variation). Except for the performances of the Variation by BH, the correlations are lower than those reported in the "Träumerei" study. We think that the differences can be attributed to the character of the pieces and the method of measurement used. The performers differed considerably in their reliability to replicate performances: BH was the most consistent. The difference in reliability may have been due to the fact that BH used a deeper rubato (comparable to that of the "Träumerei" performers). A deeper rubato raises the intended timing signal over the level of timing noise and thus raises the correlations artificially. Correlating the timing patterns of the two performers (on average .56 for the Theme and .61 for the Variation, both at medium tempo) indicates indeed that they did not behave in the same way.

Chosen tempi

The tempi chosen by the performers are given in Table 1. The values were derived from the duration of the piece

[3] Using a linear scale would raise the correlations (with a maximum increase of .1 and an average of .03) compared to (sampled) log data – biassing results toward relational invariance. Repp initially used linear IOIs in calculating correlations

[4] Using average performances would raise all correlations systematically (with a maximum of .12 and an average of around .08) compared to (sampled, linear) individual performance data – again biassing results toward relational invariance

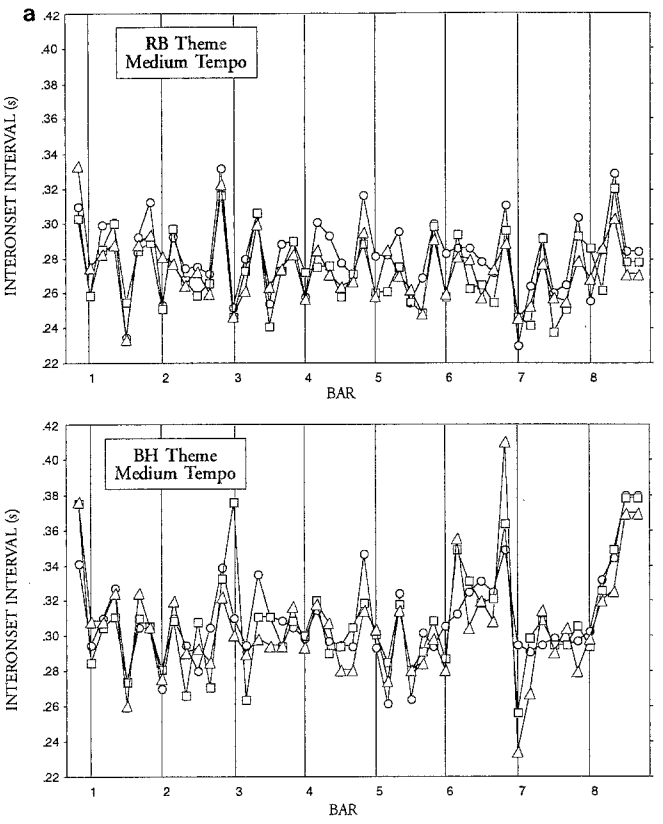

Fig. 4a. Timing patterns of eight bars of the Theme by the two pianists at the medium tempo (three repeated performances)

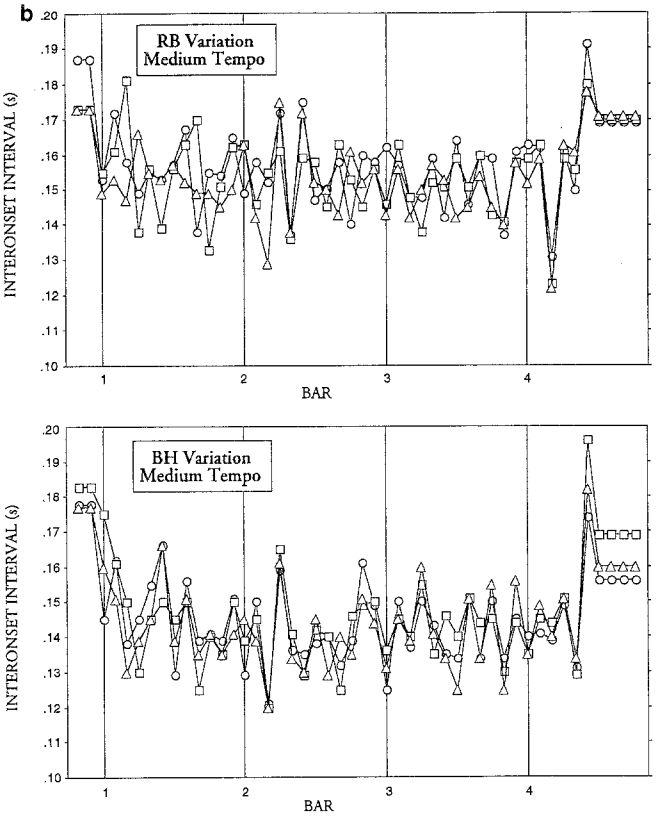

Fig. 4b. Timing patterns of four bars of the Variation by the two pianists at the medium tempo (three repeated performances)

Table 1. Average tempi chosen by the performers and the average tempi range (tempo) indicared in M.M. (Maelzel's Metronome) for a dotted quarter note)

		tempo			
piece	performer	fast	medium	slow	range
Theme	RB	75.4	58.1	50.7	0.87–1.30
	BH	65.0	50.6	40.6	0.80–1.29
Variation	RB	59.4	52.5	42.9	0.82–1.13
	BH	59.9	50.7	31.8	0.63–1.18

(from the onset of the first note to the onset of the last note). Over repeated performances at the same intended tempo, the tempi differed by less then 1.4% from the mean, except for BH's fast performances of the theme, which had a range of 2.5%. The last column gives the range of tempi used as the ratio's slow/medium and fast/medium. These ranges constitute a larger range of tempi than in the "Träumerei" study, in which the average was 0.85–1.15.[5]

[5] The ranges may not be not strictly comparable because in the "Träumerei" study the tempi were estimated, not measured, by means of a metronome. The determination of the global tempo is an acknowledged problem in itself (see, e.g., Repp, submitted).

Table 2. Average correlations between performances

			tempo		
piece	performer	tempo	fast	medium	slow
Theme	RB	fast	.84	–	–
		medium	.75	.81	–
		slow	.69	.80	.89
	BH	fast	.84	–	–
		medium	.73	.86	–
		slow	.56	.81	.87
Variation	RB	fast	.80	–	–
		medium	.65	.76	–
		slow	.61	.60	.78
	BH	fast	.94	–	–
		medium	.85	.93	–
		slow	.79	.84	.91

Consistency of timing patterns

The average correlations between performances (between and within tempi) are given in Table 2, using log-transformed normalized IOIs of individual performances.

It is useful to make some observations on other patterns in Table 2 before turning to the main comparison between performances in different tempi. First, consider the within-tempo correlations (the consistency over repeated performances) per piece and per performer. One would expect the consistency between performances at the same (high or

low) extreme tempi to decrease in relation to the medium tempo, because of the smaller amount of training the pianists received in these conditions and because extreme tempi should create a more difficult task (considering motor control and mental time keeping). Table 2 shows, however, that the average correlation for extreme tempi (fast–fast and slow–slow) was .86, whereas the average medium–medium correlation was .84. Clearly the pianists chose a tempo range within which they were able to master the performance consistently and controllably.

Consistency was similar in both the Theme and the Variation. Both pieces showed an average correlation between performances of .79. This is surprising, considering the more elaborate rhythmical structure and performance demands of the Theme.

BH replicated his performances more reliably than RB. The average correlation between performances of BH was .83, and the average correlation between performances of RB was .75.

The main question is, "Do the expressive timing profiles of the performances change at different tempi?" To answer, we have compared the average correlation between the slow–fast tempo extremes (.66) with the correlation between same tempo (fast–fast, medium–medium, slow–slow) performances (.85). To test for significance, we considered the individual correlations, not their average. For the Variation, all individual correlations of performances between the tempo extremes were significantly lower ($p < .05$, $N = 221$, Fisher Z transform) than any correlation between performances of the same piece by the same performer at the same tempo. Thus, we conclude that a change in global tempo affected the shape of the timing profile, evidence counter to relational invariance. For the Theme, not all comparisons were significant (which may reflect the small number of data points, $N = 48$).

Analysis of variance (ANOVA)

The between-tempo correlation suggests a linear relation between expressive timing profiles at different tempi. But this measure does not differentiate between an additive and a multiplicative model; that is, the high correlation does not refute the hypothesis that a timing profile is a motor program with a parameter yet to be determined that sets the global playback speed, the multiplicative-rate parameter hypothesis.

The high between-tempo correlation provides no evidence to prefer that hypothesis to a model with an additive component, e.g., the purely additive event-shift model (Bilmes, 1993) in which timing is absolutely invariant with tempo. Repp (1994) has acknowledged the point and used an ANOVA on log-transformed IOIs. If the log-transformed timing profiles for different tempi are parallel, then the IOI by tempo interaction should be nonsignificant. Accordingly, separate ANOVAs per piece and per performer were conducted. In our study, each ANOVA had IOI Number (113 levels for the Theme, 223 for the Variation) and Tempo (3 levels) as fixed factors and Performance within tempo as a random factor. The IOI × Tempo interactions from ANOVAs of the performances were significant for the Theme of RB, $F(224,678) = 2.122$, $p < .0001$, and BH, $F(224,678) = 4.128$, $p < .0001$; and for the Variation of RB, $F(444,1338) = 3.022$, $p < .0001$, and BH, $F(444,1338) = 4.444$, $p < .0001$. Because of the significant interactions between tempo and IOI, we conclude that expressive timing in the performances of the Theme and Variation was not a relational invariant. Our results are not consistent with the findings reported in the "Träumerei" study which used the same method. We shall leave a possible explanation to the general conclusion.

Grace-note timing patterns

One of the motivations for our choice of the Beethoven variations was the number of grace notes in the Theme. They are all notated in the same way in the score (see Figure 1 a, in which the grace notes are numbered in square boxes). The grace notes occur in five different rhythmical contexts: I (grace note nos. 2 and 10), II (nos. 3 and 11), III (4 and 5) IV (1, 6, and 9), and V (7 and 8). The grace notes in context I can be characterized as *Appogiatura* (time-taking grace notes), because of their pitch interval from the next note and because of the derivation of the singing style of the Theme (comparable to the grace notes notated as small eighth notes in the "Träumerei" score). The grace notes in the other contexts can be characterized as *Acciaccaturra* (timeless grace notes).

We looked in detail at the individual grace notes in the rhythmical contexts I, II, and III for BH (Figures 5, 6, and 7). In each Figure, the data of the nine performances of one grace note is depicted. The horizontal axis shows the average beat duration of the performance. The vertical axis depicts the duration of the specific grace note in that performance. The duration of a grace note is defined as the IOI between the onset of the grace note and the onset of the note to which it is attached. Each figure has a different vertical scale. The tempo scaling predicted from the average beat duration in the medium tempo is plotted as a reference line. If a grace-note IOI scales proportionally with global tempo, then it should be close to this line. Visual inspection indicates that replications are quite accurate: same-tempo grace notes are about the same length. Relational invariance is violated consistently: in almost all cases, low and high tempo grace notes were not close to the reference line.

Figure 5 plots the timing patterns of grace notes 2 and 10. Both seem to scale proportionally from the medium to the fast tempo. But from the medium to the slow tempo, BH exaggerates the timing of the grace note with respect to the global tempo.

Grace notes 3 and 11 (see Figure 6) are clearly different. They stay invariant from the medium to the fast tempo, less so from the medium to the slow tempo. The maximum deviation over all tempi is 10 ms.[6]

[6] The shortness of this time interval indicates that the time resulution of 5 ms used in the "Träumerei" study is too coarse for measuring or determining possible relational invariance here

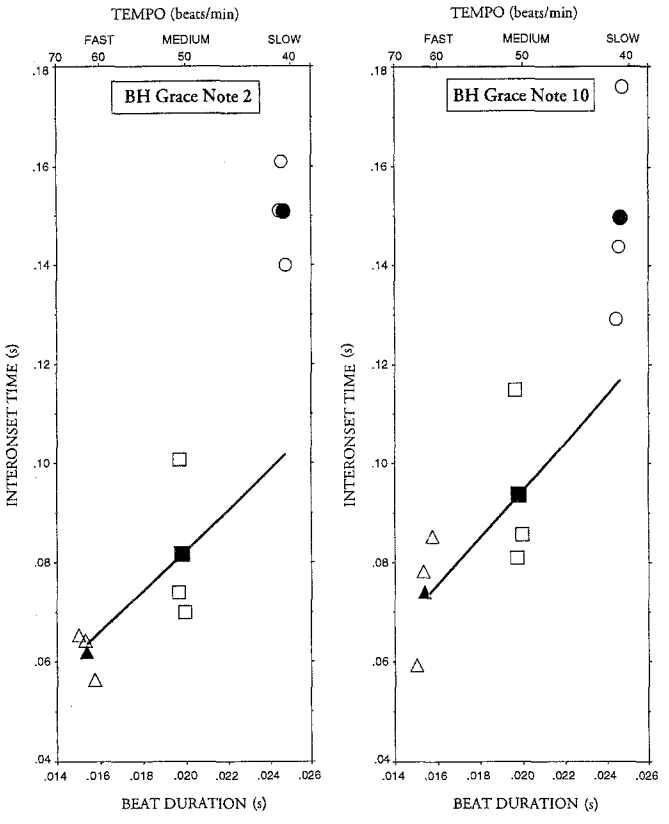

Fig. 5. Timing of grace notes 2 and 10 for three repeated performances in the three tempi. (○ = IOIs slow tempo; □ = IOIs medium tempo; △ = IOIs fast tempo; ● = Mean IOI slow tempo; ■ = Mean IOI medium tempo; ▲ = Mean IOI fast tempo; ▬ = Predicted IOI in case of proportional scaling with respect to global tempo)

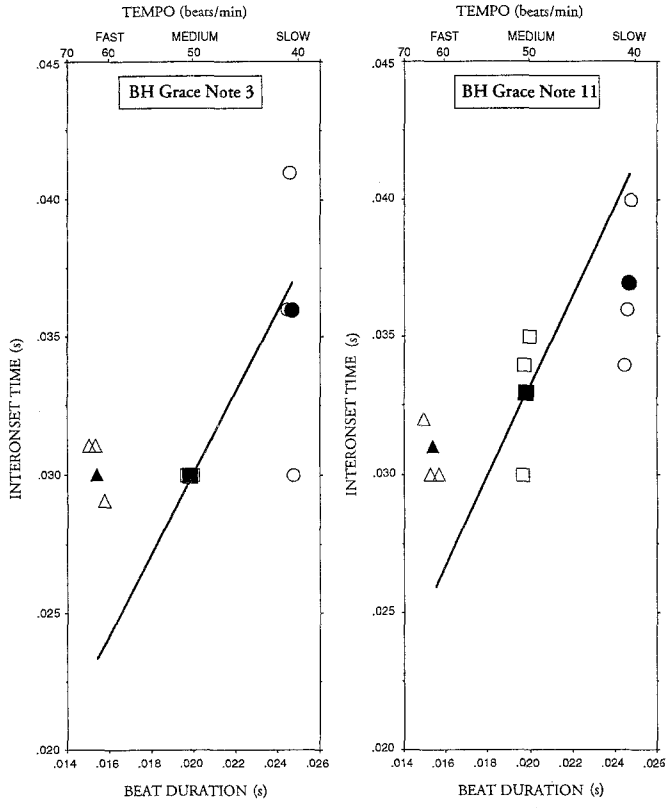

Fig. 6. Timing of grace notes 3 and 11 for three repeated performances in the three tempi

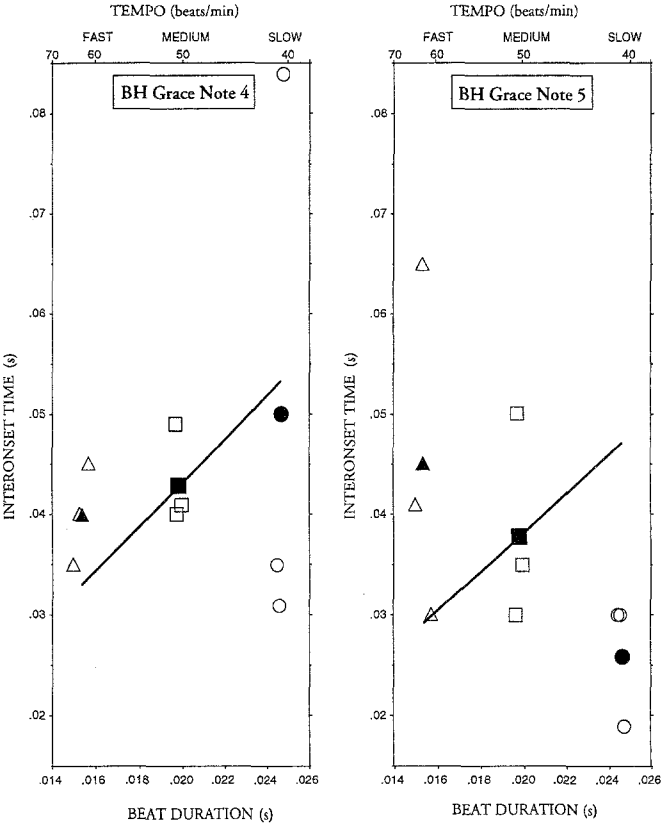

Fig. 7. Timing of grace notes 4 and 5 for three repeated performances in the three tempi

Finally, Figure 7 shows the timing of grace notes 4 and 5. Grace note 5 is remarkable in that it scales inversely with the tempo. So there was more to the timing of grace notes than proportional scaling. But of course, more data are needed to come to a precise description and explanation of these different behaviors of grace notes.

These observations were confirmed by a significant interaction between IOI and tempo for ANOVAs over all log-transformed grace-note IOIs in the theme for both performers. The IOI × Tempo interactions from ANOVAs of the grace notes of the Theme were significant for both RB, $F(20,66) = 4.352$, $p < .0001$, and BH, $F(20,66) = 3.242$, $p < .0002$.

General discussion and conclusion

In this study we analyzed the implications of a tempo curve as a representation of time in music cognition research, a notion that is present in several models of timing and analysis methods (e.g., Clynes, 1987; Feldman, Epstein, & Richards, 1992; Sundberg & Verillo, 1980; Todd, 1989). Our analysis suggests that the idea has little cognitive, perceptual, or musical reality. The analysis of the expressive timing profiles for performances of two works from Beethoven's Variations (WoO 70) showed that timing in general did not scale proportionally with global tempo. We take the results as evidence against the notion of an overall tempo curve.

The present results conflict with those in the "Träumerei" study. There are several possible reasons for the difference. First, the musical structure of the pieces was different in the studies. Schumann's "Träumerei" is a slow, expressive piece from the Romantic period, with a prominent harmonic and melodic structure, but rhythmically vague. Of the Beethoven pieces, the Theme has a very clear rhythmical structure and a number of characteristic ornaments, but the Variation is similar to "Träumerei" because, although the tempo of the Variation is higher, both consist mainly of sixteenth notes and have little or no rhythmic variation or ornaments. Nonetheless, even in the Variation we found significant differences in expressive timing between different global tempi.

Second, the range of tempi chosen by the subjects may have contributed to the difference in results. For "Träumerei", the extreme tempi differed on average by 15% from the medium tempo; in the Beethoven pieces, by contrast, the range was double that size. By measuring the consistency of repeated performances, we showed that the performances at extreme tempi were still under the control of the performers, and our measurements indicated a systematic breakdown of relational invariance at these more extreme tempi.

Finally, some methodological issues of data collection and analysis deserve comment. The method of deriving IOIs from the measured data (note onsets) influences the data analyses. While these issues may be relatively unimportant for Repp's (1994) results, without careful consideration they would have distorted the conclusions in our case.

In the "Träumerei" study, relational invariance holds for a piece "with expressive gestures on an even rhythmical flow." In both the "Träumerei" study and the present work, evidence is inconsistent with the relational-invariance hypothesis, particularly evidence concerning the structural aspects of the music (chord spread, note overlap, and certain types of ornaments). Hence, separate analysis of the timing contributions of the structural aspects of music is one promising route to be taken in future research. Our study has considered grace notes, but invariance is still an open question for concepts such as meter, phrase structure, and surface structure. It is not unrealistic to assume that these components behave differently when scaled in global tempo.

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References

Bilmes, J. A. (1993). Timing is of the essence: perceptual and computational techniques for representing, learning, and reproducing expressive timing in percussive rhythm. MSc Thesis. Cambridge: MIT.

Brendel, A. (1991). *Theme and Variations II. Schumann – Beethoven.* Liner Notes for CD (Philips 432093-2).

Clynes, M. (1987). What can a musician learn about music performance from newly discovered microstructure principles (PM and PAS)? In A. Gabrielsson (Ed.), *Action and perception in rhythm and music.* Royal Swedish Academy of Music, No. 55, 201–233.

Desain, P., & Honing, H. (1992). *Music, mind and machine: Studies in computer music, music cognition and artificial intelligence.* Amsterdam: Thesis Publishers.

Desain, P., & Honing, H. (1993). Tempo curves considered harmful. In J. D. Kramer (Ed.), Time in contemporary music thought, *Contemporary Music Review.* 7(2), 123–138. London: Harwood Press. Reprinted in Desain & Honing (1992).

Drake, C., & Palmer, C. (1993). Accent structures in music performance. *Music Perception, 10(3),* 343–378.

Feldman, J., Epstein, D., & Richards, W. (1992). Force dynamics of tempo change in music. *Music Perception, 10(2),* 185–204.

Gibson, J. J. (1975). Events are perceivable but time is not. In J. T. Fraser & N. Lawrence (Eds.), *Study of time, 2.* Berlin: Springer Verlag.

Honing, H. (1990). POCO: An Environment for Analysing, Modifying, and Generating Expression in Music. In *Proceeedings of the 1990 International Computer Music Conference,* 364–368. San Francisco: Computer Music Association. Reprinted in Desain & Honing (1992).

International MIDI Association (1983). *MIDI musical instrument digital interface specification 1.0.* North Hollywood: International MIDI Association.

Nakajima, Y., ten Hoopen, G., & van der Wilk, R. (1991). A new illusion of time perception. *Music Perception 8,* 431–448.

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. (1994). Relational invariance of expressive microstructure across global tempo changes in music performance: An Exploratory Study, *Psychological Research/Psychologische Forschung, 56,* 269–284.

Repp, B. H. (submitted) On determining the global tempo of a temporally modulated musical performance.

Sundberg, J., & Verillo, V. (1980). On the anatomy of the ritard: A study of timing in music. *Journal of the Acoustical Society of America. 68,* 772–779.

Todd, N. (1989). A computational model of rubato. In E. Clarke & S. Emmerson (Eds.), Music, Mind and Structure, *Contemporary Music Review, 3(1),* 69–88.