

## Variability of timing in expressive piano performance increases with interval duration

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In simple motor tasks such as finger tapping at different constant rates, within-trial variability of response interonset intervals (IOIs) increases with IOI duration (which varies between trials). In expressive piano performance, the rate of key depressions is not constant, in part due to compositional structure and in part due to expressive timing, so that IOIs of many different durations occur within a single "trial." Nevertheless, across repeated performances of the same music (Schumann's "Träumerei" and Debussy's "La fille aux cheveux de lin") at the same intended tempo, the standard deviations of individual IOIs tend to increase linearly with their average duration. This is also true when the variation is due to expressive timing alone and when unintended differences in basic tempo between performances are taken into account. In the music studied here, at least, there was no evidence of compensatory timing. The results suggest that the pianists employed a continuously variable tempo governed by a flexible internal timekeeper whose variability follows a generalized Weber's law (for IOIs longer than about 300 msec).

In a rhythmic motor task such as finger tapping, the variability of response interonset intervals (IOIs) typically increases with IOI duration, just as the perceptual difference limen in a temporal discrimination task increases with stimulus IOI duration. Between about 300 and 2,000 msec, the increase in the perceptual difference limen tends to be linear, so that a generalized form of Weber's law (i.e., including a constant term) holds, with a Weber fraction of about 4%–6% for trained listeners (Drake & Botte, 1993; Friberg & Sundberg, 1995; Getty, 1975). The form of the relationship in motor production tasks is less firmly established, although most recent studies have shown the standard deviation to increase linearly with IOI duration between 300 and 2,000 msec (e.g., Church, Lacourse, & Collyer, 1997; Ivry & Hazeltine, 1995; Peters, 1989), with Weber fractions of 3%–5%, which nicely parallels the perceptual results. However, it has also been claimed that the timing variance, not the standard deviation, increases linearly with IOI duration (Wing & Kristofferson, 1973), that the standard deviation increases as a power function of IOI duration (Michon, 1967), and that there is a minimum of variability around 700 msec (Woodrow, 1932).

Wing and Kristofferson (1973) made an important distinction between timekeeper variance and motor variance. Only the former varies with IOI duration, whereas the latter is assumed to be constant. At IOIs shorter than 300 msec, there is an increase in relative variability in pro-

duction tasks (Peters, 1989), which may be due to the motor variance exceeding the timekeeper variance, although other factors may play a role as well. A change in the relationship between variability and IOI duration around 250–300 msec has also been observed in perception (Friberg & Sundberg, 1995; Hibi, 1983; ten Hoopen et al., 1995), where it has been attributed to a fixed sensory noise component that exceeds the timekeeper variability at short intervals (Ekman, 1959). Variability also increases greatly for IOI durations beyond 2 sec, presumably because they exceed a limit of perceptual integration, so that the feeling of rhythmicity is lost (Woodrow, 1932). Thus, both perception and production of temporal intervals seem to be limited by system noise at short IOIs, by the increasing variability of a central timekeeping mechanism at intermediate IOIs and by a sensory short-term memory at long IOIs. The central timekeeper is likely to be the same in perception and production (Ivry & Hazeltine, 1995).

Nearly all the data on response timing variability have been obtained with single intervals or uniform (isochronous) sequences. There are few studies of variability using metrical sequences containing intervals of different duration. Variability in such sequences may be constrained by the establishment of a rhythmic hierarchy. Shorter intervals subdividing a longer interval may exhibit temporal compensation, so that the variance of their sum is less than the sum of their individual variances. This has often been observed in speech production tasks (e.g., Kozhevnikov & Chistovich, 1965; Martin, 1972). Also, longer IOIs may be mentally subdivided, which can reduce variability (Yee, Holleran, & Jones, 1994). However, such strategies generally presuppose integral ratios among different IOI durations.

The present study examined whether a systematic relationship between IOI duration and variability holds in

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expressive music performance, perhaps the most complex form of controlled timing in human motor action. Most music contains notes (and rests) of different, integrally related values, so that the IOI durations within a single performance vary over a considerable range. In addition, however, an expressive performance is characterized by expressive variations in timing that seriously perturb the integral relationships among IOIs (e.g., Gabrielsson, 1987; Palmer, 1989; Repp, 1992b; Seashore, 1938/1967) and result in a more nearly continuous distribution of IOI values (see Repp, 1995b). Expressive timing is linked to the musical structure, and its pattern tends to be quite consistent across an artist's repeated performances of the same music (Palmer, 1989; Repp, 1995a; Shaffer, Clarke, & Todd, 1985), but, of course, it is not replicated exactly. While previous studies of music performance have focused mostly on the overall systematicity and replicability of expressive timing, its local degree of precision is examined here. In particular, the question is whether timing variability increases with IOI duration: Are longer IOIs less accurately reproduced in repeated performances of the same music than are short IOIs?

MacKenzie and Van Eerd (1990), in a study of pianists' playing of scales at various fast tempi, found, on the contrary, that variability increased as IOI duration decreased. However, this was almost certainly due to the short durations of the intervals concerned (less than 250 msec), where motor limitations and ergonomic factors such as inequality among the fingers play an important role. Also, the result was obtained by comparing different tempo conditions (as in finger tapping tasks), and the pianists' intention was to play as evenly as possible, not expressively. More relevant to the present study is an analysis by Shaffer et al. (1985) of a concert pianist's expressive performances of a piece by Satie. Focusing on a short passage of music that was played nine times, Shaffer et al. observed that the Weber fractions (coefficients of variation) tended to be larger for short IOIs than for long IOIs. However, the standard deviations (which can be calculated from the data displayed below their Figure 2 on p. 71) clearly increased with IOI duration in approximately linear fashion, at least at the longer IOIs (> 500 msec). There was a considerable range of variabilities for short IOIs, probably due to their short duration (< 300 msec) and to the fact that they were nested within regularly marked half-beats of 1–1.2 sec in duration, which may have constituted the primary level of timing control. The style of this music did not invite large expressive timing variations and instead encouraged hierarchical metrical control; indeed, Shaffer et al. attributed the timing of notes within beats to "motor procedures" rather than to a central timekeeping mechanism. In such a situation, temporal compensation among short IOIs may be observed.

The present study, by contrast, focuses on music by Schumann and Debussy in which metrical structure plays a less prominent role, giving the performer greater freedom in expressive timing. Here, the tempo may be considered to be continuously variable and governed by a flexible timing mechanism (Shaffer, 1981; Shaffer et al.,

1985). If the accuracy of this timekeeper decreases with the interevent interval duration, then the standard deviation of individual IOIs across repeated performances should increase monotonically, perhaps linearly, with IOI duration. Any effects of hierarchical metrical organization would perturb this relationship, especially at shorter IOI durations. The purpose of this brief study, then, was to examine whether a generalized Weber's law holds in highly expressive, relatively ametrical piano performance.

Ideally, a large number of repeated performances of the same music by the same artist would be required to obtain stable estimates of the variability of individual IOIs. This is difficult to obtain, and artists may be tempted to vary their interpretation if there are many takes. Instead, this study made use of previously recorded performances of two pieces, representing three takes from each of 10 pianists. While the estimates of IOI variabilities for each individual pianist were not very reliable, they were more stable when averaged across all pianists and still meaningful, given that the pianists' individual patterns of IOI durations were quite similar. Thus, it was possible to obtain a reasonable view of the relationship between IOI duration and variability.

## METHOD

The performances were drawn from a small MIDI database compiled by the author several years ago. It comprised four pieces, played three times (only twice, in one case) by 10 graduate student pianists from the score after a brief rehearsal, with instructions not to change the interpretation. The performances were recorded in MIDI format from a Yamaha Disklavier MX100A upright piano. Repeated performances of the same music were separated by about 15 min, during which the other pieces were played. Although the performances were not of recital quality, given the limited preparation, they were all fluent and expressive. Only two of the pieces were considered here: "Träumerei" from "Kinderszenen" (op. 15) by Robert Schumann and "La fille aux cheveux de lin" from Book I of the Preludes by Claude Debussy.<sup>1</sup>

The music was considered as a time series of events, each composed of one or more nominally simultaneous (but actually somewhat asynchronous) note onsets. The IOIs in each performance were computed from the registered MIDI note onset (i.e., hammer-string contact) times, considering only the highest note in each nominal chord or simultaneity. Grace notes were disregarded. There are 214 successive IOIs in the Schumann piece, most of which correspond to eighth-note intervals in the score, but some of which correspond to longer notated intervals. There are 241 IOIs in the Debussy piece, representing sixteenth-note, eighth-note, and longer intervals. Detailed analyses of the expressive timing in both pieces have been reported elsewhere (Repp, 1995a, in press-b). They included principal component analyses of the pianists' timing profiles (IOI vectors), to determine whether more than a single timing pattern was represented. For both pieces, the first principal component accounted for most of the timing variance, and all performances showed high positive correlations with each other. This justifies the averaging of IOI durations across all pianists.

For each piece, the standard deviation of each individual IOI was calculated across the three performances of each pianist, and, subsequently, the median of each of these standard deviations was determined across the 10 pianists. The median was preferred over the mean because there were isolated instances of unusually high variability.

## RESULTS

Figure 1 shows these median within-pianist standard deviations as a function of average IOI duration for each

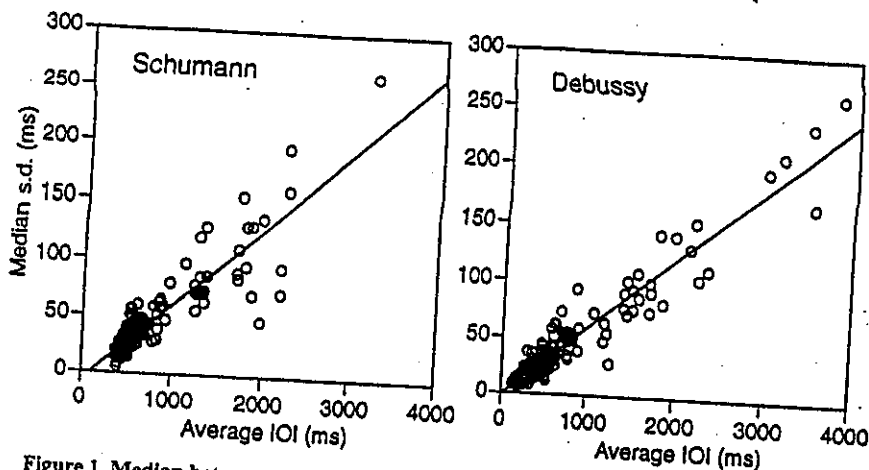


Figure 1. Median between-performance standard deviations as a function of average IOI duration for the Schumann and Debussy pieces.

piece. It is evident that there is a linear relationship in each case. The linear regression accounts for 82% of the variance in the Schumann piece ( $r = .90$ ) and for 92% in the Debussy piece ( $r = .96$ ). The slopes of the regression lines for the two pieces are similar (.068 and .062, respectively), and their intercepts are not far from zero, so that Weber's law may be said to hold approximately, with an average Weber fraction of about 5%.

The IOI durations plotted along the abscissa include two sources of variation: differences in notated interval duration and differences due to expressive timing. Expressive timing cannot be removed from the data, but notational differences can be removed by normalizing the IOIs. Normalized IOI durations and standard deviations were obtained by dividing each IOI and its standard deviation by the number of eighth notes it nominally contained in the Schumann and by the number of sixteenth notes it nominally contained in the Debussy, these being the smallest note values in the respective scores. The variation in normalized IOI durations and standard deviations is due to expressive timing alone. Figure 2 plots these normalized values against each other. Again, a linear relationship can be seen, accounting for 82% of the variance in the Schumann ( $r = .90$ ) and for 76% in the Debussy ( $r = .87$ ). The slopes of the regression lines are again similar for both pieces (.092 and .086, respectively), even though the range of normalized IOI durations in the Debussy piece is only about half of that in the Schumann piece. Both functions have negative intercepts, which suggests a nonlinearity at very short durations and a deviation from strict proportionality. However, a generalized version of Weber's law—that is, a linear relationship with a nonzero intercept (Getty, 1975; Ivry & Hazeltine, 1995)—does seem to hold.<sup>2</sup> The Weber fraction (coefficient of variation) tends to increase with IOI duration, reaching about 8% for the longest IOIs.

Linear regressions were also computed separately for different nominal IOI sizes. In the Schumann piece, the linear relationship was almost entirely due to eighth-note intervals, which constituted the large majority of IOIs.

The average normalized durations of notationally longer IOIs, with the exception of one IOI containing an arpeggiated chord, varied over a surprisingly small range and therefore contributed little to the linear relationship. In the Debussy piece, very similar regression lines and correlations were obtained in separate analyses of sixteenth-note, eighth-note, and longer intervals; thus, the right panel of Figure 2 is representative of all nominal IOI sizes. In addition, it was observed that all individual pianists exhibited significant positive correlations (ranging from .35 to .73) between normalized IOI durations and standard deviations in both pieces.

One possible complication is that the basic tempo of the repeated performances may not have been identical. Although the pianists tried to replicate their interpretation, some unintended variation in basic tempo was unavoidable. This variation entails a linear increase in IOI variability with IOI duration across performances: Since a change in basic tempo effectively scales the IOIs by a multiplicative factor, IOI standard deviations across performances will increase as a constant proportion of IOI duration.<sup>3</sup> Could the relationship shown in Figure 2 be due to changes in basic tempo alone? A rough (inverse) measure of basic tempo of each individual performance was obtained by computing its average normalized IOI duration, and the standard deviation of this duration across the three performances of each pianist was determined. The average of these standard deviations across the 10 pianists yielded a measure of the average variability in basic tempo across repeated performances, and the grand-average normalized IOI duration yielded an estimate of the average (inverse) tempo of all pianists' performances. The coefficient of variation obtained by dividing these two quantities was almost exactly .02 in each of the two pieces. The dashed line in each panel of Figure 2 shows this linear increase in IOI variability expected on the basis of unintended between-performance variation in basic tempo. Clearly, the actual variabilities are larger and the slope of the regression line is steeper, which means that a substantial part of the increase is related to

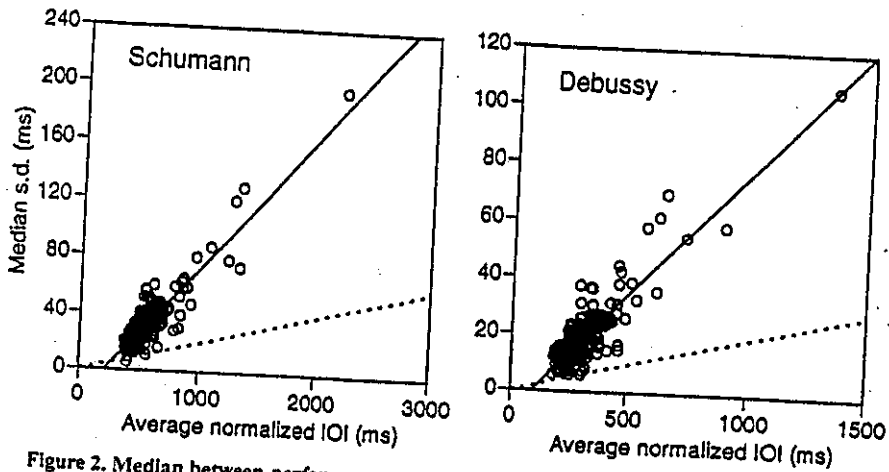


Figure 2. Median between-performance standard deviations as a function of average normalized IOI duration for the Schumann and Debussy pieces. The dashed line indicates the increase in variability expected on the basis of unintended between-performance variation in basic tempo.

the within-performance variation in IOI duration caused by expressive timing.

Finally, although the linear relationships obtained leave little room for compensatory timing, an analysis was performed on the most likely candidates for such a strategy: the sixteenth-note IOIs in the Debussy piece. They occur in pairs as well as in longer sequences. The sequences were divided into pairs, and the standard deviation of the total duration of each pair was determined, separately for each pianist. These effective eighth-note IOI standard deviations were then plotted against the root-mean-square standard deviation of the two component sixteenth-note IOIs. If there was compensatory timing, the linear relationship between these two measures of variability should have a slope of less than 1, indicating that the variance of the sum of two sixteenth-note IOIs is less than the sum of their variances. However, the slopes were larger than 1 for all 10 pianists, ranging from 1.02 to 1.20. Thus, the durations of successive sixteenth-note IOIs tended to be positively correlated; there was no compensatory timing even at this lowest level in the metrical hierarchy.

## DISCUSSION

The results suggest that, in highly expressive, nearly ametrical music performance, a pianist's precision of timing decreases with the duration of the interval that is produced. The findings are in agreement with the operation of a generalized Weber's law in motor production tasks, and they extend this principle from simple finger tapping (e.g., Ivry & Hazeltine, 1995; Peters, 1989) to complex keyboard performance in which the IOIs are continuously variable rather than fixed, due to expressive timing. The results are also consistent with flexible timing models of expressive music performance according to which the metrical structure is cognitively deformed prior to execution and then is paced by a flexible timekeeper (Shaffer et al., 1985). It appears that the accuracy of this timekeeper decreases as a function of the IOI being timed, at least above 300 msec or so, just as the accuracy of a rigid timekeeper does. Although expressive timing can be modeled in terms of several hierarchically nested temporal processes (Todd, 1985, 1995), the variability at higher levels, which extend over rela-

tively long stretches of time, is presumably much larger than that at the lowest level; therefore, the observed variability reflects the lowest level only.

In less expressive music that exhibits a more rigid metrical structure, such as a dance rhythm, compensatory timing may be observed at the level of short IOIs. In the present pieces, however, this played no role; the expressive timing reflected a relatively free succession of melodic-rhythmic gestures. It is likely that expressive timing and metrical subdivision are, to some extent, mutually exclusive, since the latter depends on the integral relationships that the former destroys.

Most likely, there is an increase in the perceptual difference limen that parallels the increase in production variability with IOI duration. That is, in listening to an expressive music performance, long IOIs are likely to be perceived and evaluated less accurately than are short IOIs. There is limited evidence from perceptual studies in support of this hypothesis (Repp, 1992a, 1997, in press-a).

One limitation of the present data should be acknowledged: The pianists were skilled but relatively inexperienced, and the performances were only minimally rehearsed. Most likely, well-rehearsed performances by experienced concert artists will exhibit less variability in absolute terms, provided that the artists' intention is to reproduce their interpretation exactly. It is conceivable that highly accomplished musicians have available methods of timing control that differ qualitatively from those of young pianists (see Epstein, 1995). However, it is doubtful that they are exempt from the relationship between interval duration and variability demonstrated here, which seems to be a general law governing timing in perception and production, perhaps deriving from a high-frequency mental oscillator or pacemaker (see, e.g., Treisman, Faulkner, & Naish, 1992) whose variability accumulates as IOI duration increases.

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## NOTES

1. The other two pieces were less well suited for the present investigation because one has a steady metrical pulse and the other contains many arpeggiated chords. Also, their data have been only partially analyzed.
2. The generalized Weber's law is often formulated in terms of variances and squared IOIs rather than standard deviations and IOIs (see Ivry & Hazeltine, 1995). However, plots of median variances against squared IOIs look extremely similar to the plots shown, which are preferred because they are easier to understand.
3. While uniform multiplicative scaling may break down at larger, intended tempo changes (see Desain & Honing, 1994; Repp, 1994, 1995b), it may be assumed to hold for small, unintended tempo differences.

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