Perception & Psychophysics
2004, 66 (4), 545-562

Timing variations in music performance: Musical communication, perceptual compensation, and/or motor control?

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A *perceptual performance* paradigm was designed to disentangle the timing variations in music performance that are due to perceptual compensation, motor control, and musical communication. First, pianists perceptually adjusted the interonset intervals of three excerpts so that they sounded regular. These adjustments deviated systematically from regularity, highlighting two sources of perceptual biases in time perception: rhythmic grouping and a psychoacoustic intensity effect. Then the participants performed the excerpts on the piano in the same regular way. The intensity effect disappeared, and some variations due to motor constraints were observed in relation to rhythmic groups. Finally, the participants performed the excerpts musically. Variations due to musical communication involved additional group-final lengthening that reflected the hierarchical grouping structure of the excerpts. These results underline the nuclear role of grouping in musical time perception and production.

Music performance involves a wide range of perceptual, cognitive, and motor abilities (for reviews, see Gabrielsson, 1999; Palmer, 1997). It is thus a thrilling research field, but also a difficult one: Music performance is unconstrained and multidimensional (Sloboda, 1988). Indeed, a musical score is not intended to be played exactly as written, and a given piece may be played in many different acceptable ways. Music performance is multidimensional because, for example, several acoustical dimensions may be varied simultaneously: Pianists use (1) timing variations (variations in inter-onset intervals [IOIs]), (2) articulation (variations in the degree of separation [staccato] or overlap [legato] of successive events), (3) chord asynchronies (variations in the degree of simultaneity of tones within chords), and (4) dynamics (variations in the intensity of tones).

This multidimensionality partly explains why music performance is so unconstrained, even when performers agree on a particular *interpretation*. An event n (see Figure 1) may be highlighted by playing the preceding one more staccato [shorter $d(n-1)$ in relation to IOI$(n-1)$], by delaying the onset of the particular event [longer IOI$(n-1)$], or by playing it more legato [longer $d(n)$ in relation to IOI(n)], longer [longer IOI(n)], or louder (e.g., Drake & Palmer, 1993; Seashore, 1936, 1938/1967; Sloboda, 1985). In practice, performers choose a combination of these, depending on the style of the music, personal preference, and so forth—all additional dimensions of music performance.

In previous research, musicians have been asked to play at a specific tempo, in a mechanical or exaggerated way, or so as to convey specific emotions (e.g., Gabrielsson, 1974; Juslin & Madison, 1999; Palmer, 1996; Repp, 1999a). However, the multidimensionality mentioned above has remained: Several expressive dimensions have varied simultaneously. We present a paradigm that constrains musicians to use one dimension. It was used in the present study to investigate timing variations.

The Origin of Timing Variations

Timing variations have usually been explained by a *musical communication hypothesis*, the idea being that they communicate the musical structure and emotions to listeners. A *perceptual hypothesis* and a *motor control hypothesis* have also been proposed, according to which timing variations originate from perceptual and motor constraints, respectively. Experimental evidence for these nonexclusive hypotheses will be considered in turn, with emphasis on the last two, which are less obvious and more recent.

The musical communication hypothesis. The view that timing variations correspond to the performer's interpretation of the musical structure and its communication to the listener has dominated the literature (e.g., Clarke, 1985; Gabrielsson, 1987; Palmer, 1989, 1996; Penel &

This work was part of the first author's doctoral dissertation, supported by a fellowship in cognitive sciences from the French Ministry of Education and Research. The manuscript was revised while she was supported by a music cognition postdoctoral fellowship at the Ohio State University Psychology Department and then by a postdoctoral fellowship at Cold Spring Harbor Laboratory. The authors are grateful to Bruno H. Repp, Neil P. McAngus Todd, and two anonymous reviewers for comments on earlier versions of this article. Correspondence concerning this article should be addressed to A. Penel, Cold Spring Harbor Laboratory, Freeman Building, 1 Bungtown Road, P .O. Box 100, Cold Spring Harbor, NY 11724 (e-mail: penel@cshl.edu).

Note—This article was accepted by the previous editorial team, headed by Neil Macmillan.

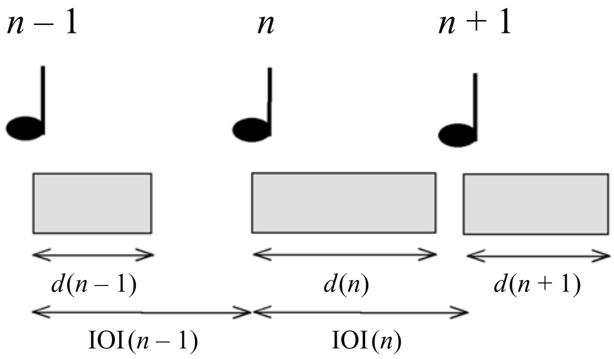

Figure 1. Illustration of event durations (*d*, duration between the onset of an event and its offset) and inter-onset intervals (IOI, duration between the onset of an event and the onset of the following one).

Drake, 1998, 2000; Seashore, 1936; Shaffer, Clarke, & Todd, 1985; Sloboda, 1985; Todd, 1992). Group-final lengthening (slowing down toward the end of a group) would communicate the hierarchical grouping structure: The degree of slowing is proportional to the group's level in the hierarchy, with greater lengthenings at higher levels (phrases, sections, and piece). Similarly, the lengthening of the first and/or last beats of bars would communicate the metrical structure, and melody lead (within a chord, the temporal precedence of the melody tone) would communicate the voice structure.

Most recently, another communicative aspect of music performance has been investigated: emotions (e.g., Juslin & Madison, 1999; Laukka & Gabrielsson, 2000). Performers have been shown to be able to communicate specific emotions, and tempo variability (thus, timing variations) is among the cues involved. We will refer to structural and emotional communication as a musical communication hypothesis for timing variations. Such timing variations originate from higher level processing, in comparison with what follows.

The perceptual compensation hypothesis. Some authors have also proposed that *some* timing variations compensate for perceptual biases: Some IOIs would be perceived as being shorter/longer than they are and, therefore, would be played so as to be longer/shorter, to restore regularity (Drake, 1993b; Penel & Drake, 1998, 1999; Repp, 1992, 1998a, 1998b, 1999b; Seashore, 1936). Perceptual biases can be due to psychoacoustic effects and/or to effects related to perceptual organization, such as grouping. Both originate from perceptual constraints; thus, the resulting timing variations derive from lower level processes than those involved in musical communication.

Psychoacoustic effects refer to the dependence of perceived time on other dimensions: A deviation in frequency or intensity can cause the perception of a deviation in time (Crowder & Neath, 1994; Jeon & Fricke, 1997; Shigeno, 1986, 1993; Tekman, 2001). Such effects have been demonstrated with simple stimuli, such as pairs of tones, but probably also generalize to music.

Pitch-based grouping does not seem to result in a bias in time perception (Drake, 1993b; Tekman, 2001). In contrast, intensity-based grouping may: Woodrow (1909) observed that in monotone sequences of alternating loud and soft tones, the IOIs preceding the loud tones had to be shorter for the sequence to be perceived as isochronous, which was confirmed by Tekman (1997), using chromatic scales (see also Repp, 1992, 1998b, using music). Both explained this as an effect of grouping: Loud tones initiate perceptual groups, and intervals between groups may be perceived to be longer (Fraisse, 1956). However, a psychoacoustic account (favored recently by Tekman, 2001) is also possible: An IOI between a soft and a loud tone would be perceived to be longer than one between a loud and a soft tone.

Finally, production and perception studies suggest that rhythmic grouping (based on temporal proximity) results in a bias in time perception. The last short IOI of a rhythmic group (a series of short IOIs surrounded by longer ones) is consistently produced longer than others (Gabrielsson, 1974); contrary to intensity-based grouping, where the IOI *between* groups is lengthened, the lengthened IOI is *within* the group here, although close to its end; see Figure 2). This group-final lengthening was observed for musicians, nonmusicians, and 5- and 7-year-old children (Drake, 1993a) and did not disappear when the pianists played mechanically (Drake & Palmer, 1993; Penel & Drake, 1998; Repp, 1999a; Seashore, 1938/1967). The last short IOI of a rhythmic group may be perceived as shorter than it is.

This was confirmed by perceptual studies. Drake, Botte, and Gérard (1989) found that the last short IOI of rhythmic groups had to be adjusted so as to be 10% longer than the others for the sequences to be perceived as regular. A temporal change (lengthening and shortening) detection task with simple rhythmic sequences led to convergent findings (Drake, 1993b): A shortening was easier and a lengthening harder to detect on the last short IOI of a rhythmic group. With a similar method, but with music, a series of studies by Repp (e.g., 1992, 1998a, 1998b, 1999b) has shown that biases in time perception are correlated with production: Lengthenings are more difficult to detect than shortenings where lengthenings typically occur in performance, and vice versa. Thus, some IOIs may be perceived as shorter/longer, and these are typically performed so as to be longer/shorter. Alternatively, the biases could simply reflect expectations about typical expressive timing, derived from experience. However, a convincing effect of musical training was not found (e.g., Repp, 1992, 1999b). Moreover, the biases appeared to be a result of on-line auditory processing, unaffected by attention and inflexible (Repp, 1998a). Close examination of Repp's data indicates that they often correspond to the last short IOI of rhythmic groups being perceived as shorter (with a lengthening difficult to detect and a shortening easy to detect) and being performed so as to be longer.

The motor control hypothesis. Finally, a *motor control hypothesis* has been proposed to explain *some* timing variations (Penel & Drake, 1999; Repp, 1999a; Seashore, 1936). We do not consider *random* variations of IOIs,

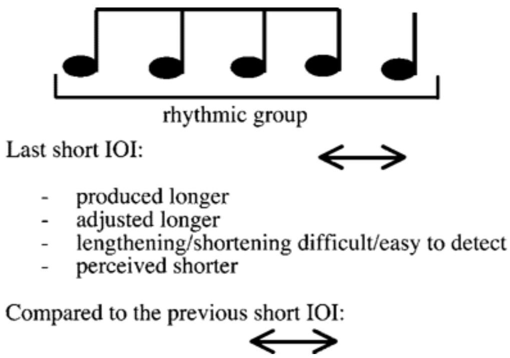

Figure 2. Schema of the rhythmic grouping effect.

which are extremely small in expert performance (Yamada, 1998). The idea is that biomechanical and instrument-related constraints may produce *systematic* variations. As for biomechanical constraints, by asking participants to tap regularly while accentuating certain taps, Billon, Semjen, and Stelmach (1996) showed that the IOI preceding the accentuated tap was shortened, whereas the following one was lengthened, as a result of timing modulations of an internal timekeeper and of faster completion of more forceful movements. As for biomechanical and instrument-related constraints, on the piano, two successive notes may be distant on the keyboard and require an extended movement, which may result in a lengthening of the corresponding IOI, especially at fast tempi. The overcoming of such constraints is part of performance expertise, but at fast tempi, timing variability in the even playing of scales has been found to be systematic and related to fingering patterns (MacKenzie & Van Eerd, 1990).

With music, Repp (1999a) also found some evidence of an influence of the physical interaction with the instrument. Pianists played in a musical and in a mechanical way and then did so in the absence of auditory feedback and in the absence of both auditory and complex kinaesthetic feedback (they tapped on a key in synchrony with an imagined performance). Timing variations in musical and mechanical performances were not affected by the absence of auditory feedback. However, the absence of both auditory and complex kinaesthetic feedback reduced the variations produced in mechanical performances and, to a lesser degree, in expressive ones. When participants synchronized with their own mechanical performances, as opposed to their expressive ones, asynchronies between taps and events and intertap intervals showed that they did not anticipate the variations they had produced; they reacted to them. These findings suggest that timing variations produced in mechanical performances have a motor origin.

The Perceptual Performance Paradigm

We pursue here the investigation of the origin of timing variations, disentangling those variations that are due to musical communication from those due to perceptual and motor constraints. A three-step *perceptual performance* paradigm was designed (Figure 3), in which an adjustment task was added to mechanical and musical performances (Drake & Palmer, 1993; Palmer, 1989; Penel & Drake, 1998; Repp, 1999a; Seashore, 1938/1967). First, participants adjust perceptually the performance parameters of each event. Typically, one dimension is chosen (timing, articulation, or dynamics, with

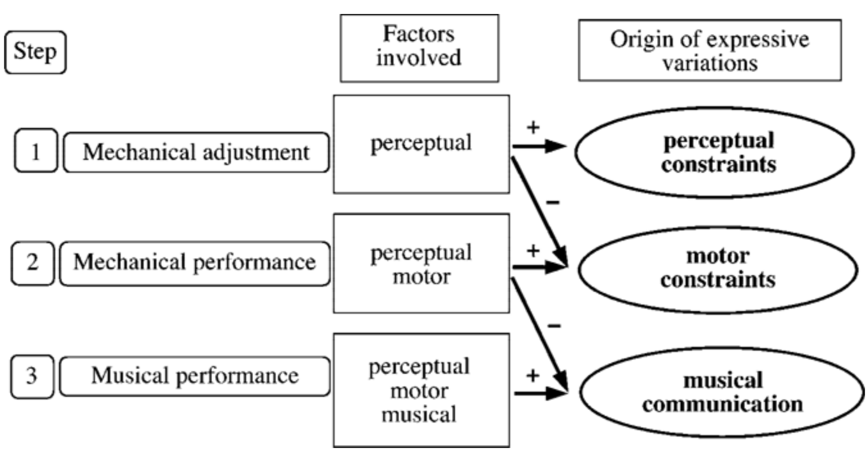

Figure 3. The rationale of the perceptual performance paradigm (see the text for details).

the other dimensions being kept constant), and the goal is a mechanical rendition of the excerpt, with the IOI, duration, and intensity of a tone corresponding to its nominal value in the score. Second, performers play on their instrument to produce the same mechanical rendition as that in the adjustment task. Third, they play the excerpt musically.

Only perceptual factors are involved in the first task. The variations in the performance that compensate for perceptual biases are measured with the systematic deviations of the mechanical adjustments from regularity. The adjustment task provides the *point of subjective equality*, whereas perceptual biases have to be inferred when a tempo change detection method is used. In the second task, both perceptual and motor constraints are involved. The variations in performance due to motor constraints are measured by comparing the mechanical performances with the mechanical adjustments. In the third task, perceptual and motor constraints, as well as musical communication factors, are involved. The variations due to musical communication are measured by comparing the musical with the mechanical performances.

This paradigm is applied in the present article to the timing dimension. We selected three fairly slow excerpts that were easy to play without much practice: a simple melody, a Brahms melody, and the latter melody with its accompaniment (previous research has suggested that perceptual biases may exhibit complex patterns due to an accompaniment; see Repp, 1998b). Five professional pianists successively adjusted mechanically, performed mechanically, and performed musically these pieces, and the timing variations that were due to perceptual and motor constraints and to musical communication were deduced. For all the excerpts, we expected a perceptual bias to arise from rhythmic grouping, with the last short IOI of such groups adjusted so as to be longer than the others. For Excerpt 3, because the chords introduce intensity differences between successive events, in addition, we expected a perceptual bias to arise from these, with soft–loud IOIs adjusted so as to be shorter than loud–soft ones. Given the participants' expertise, we did not expect additional variations in the mechanical performances, but they remained possible in light of previous research (Repp, 1999a). We previously had found some evidence that higher levels of the hierarchical grouping structure have timing effects that are under voluntary control, as opposed to lower levels (rhythmic groups; Penel & Drake, 1998). Accordingly, the mechanical adjustments and performances were expected not to reflect the hierarchy; greater group-final lengthening at higher levels should emerge only in musical performances, in which group-final lengthening might be amplified even at the lowest levels, because of additional variations communicating the grouping structure. Indeed, previous research in which mechanical and musical performances were compared has shown essentially similar timing variations in both cases, the differences being in the degree of variation (Drake & Palmer, 1993; Palmer, 1989; Penel & Drake, 1998; Repp, 1999a; Seashore, 1938/1967). Finally, Excerpt 3 was expected to show greater variations than Excerpt 2 in musical performances, since the richer material provided by the accompaniment would invite more expression.

METHOD

Participants

Five professional pianists (4 males and 1 female) took part in the experiment, with a mean age of 29 years (range from 25 to 34 years). They were piano teachers in music schools and/or accompanists and specialized in classical music.

Materials

Figure 4 shows the three excerpts. The first was a tune used in Drake and Palmer (1993), involving coinciding rhythmic, melodic, and metric accents. The second was the melody of the beginning of a Brahms Intermezzo (Opus 117, No. 1), and the third added the accompaniment to this melody. Two modifications were made to the Brahms excerpt: The last note (Excerpt 2) or chord (Excerpt 3) was lengthened to a dotted quarter-note, and the grace note preceding the second-to-last note/chord was removed. The excerpts were presented to the participants in the three tasks as displayed. Brahms's expressive slurs were kept to ensure that this would be the structure interpreted by the pianists in their musical performances (otherwise, some may have chosen a metric grouping) and to ensure that comparison would be between three task responses to identical stimuli. The pianists were familiar with the Brahms Intermezzo, but none had performed it formally before.

The tempo was 100 beats per minute for the three excerpts (i.e., a quarter-note/eighth-note lasted 600 msec in Excerpt 1/Excerpts 2 and 3, respectively). In the adjustment task, the excerpts were initially presented with random temporal irregularities.[1] All the tones were played with a constant intensity and with an interval of 10 msec between the offset of each event and the onset of the following one. This articulation was motivated by MIDI limitations (see the Apparatus section); the result sounded legato. No pedal was used.

Apparatus

The adjustment task was run on a Macintosh Quadra 650. The excerpts were played at a comfortable level over loudspeakers under control of a MAX program, making use of a Sample Cell card with a grand piano sound. The participants' adjustments were recorded by the program.

Because MIDI commands are transmitted serially and take up to 1 msec, problems of temporal precision may occur when several commands are specified at the same time. In Excerpt 3, up to 12 commands may coincide: From a chord of six tones to the following chord of six tones, there are six offsets and six onsets to be specified if legato is intended. This could result in a delay of 12 msec in the onset of a tone. The solution adopted was (1) to specify all the offsets as occurring 10 msec before the following onsets and, (2) in the chords in Excerpt 3, to send the onset command of the melody tone first and then the other onset commands in order of decreasing pitch (see Repp, 1999b).

Mechanical and musical performances were recorded on an upright Yamaha Disklavier, monitored by the Macintosh Quadra 650 with the sequencer Studiovision (the only software running at the time of recording). They were analyzed using POCO (Honing, 1990).

Procedure

The participants were tested separately in a quiet room. They did not practice the pieces before the experiment. They began with the adjustment task, being presented successively with Excerpts 1, 2, and 3. For each excerpt, they saw the score in Figure 4, featuring a

Figure 4. The three excerpts used: a simple melody (Excerpt 1; from Drake & Palmer, 1993), the melody of the beginning of a Brahms Intermezzo (Excerpt 2; Opus 117, No. 1), and the same melody with its accompaniment (Excerpt 3).

number for each IOI. On the computer screen, each number appeared above two squares: one labeled " +," and the other "−" (Figure 5). By clicking on a +/− square, the corresponding IOI was incremented/decremented by 10 msec (the participants were not informed of this step size). They could listen to the result or stop it by clicking on Play or Stop. We asked them to respect the tempo indicated by a metronome (a 100-msec-long C3, played every 600 msec), to which they could refer between adjustments. The instruction was to adjust the IOIs to obtain perfectly mechanical renditions of the excerpts, with IOIs having their nominal values according to the score and the metronome.

After the adjustment task (about 1 h), the pianists performed the excerpts on the Disklavier, first mechanically, to produce renditions of the excerpts as regular as those in the perceptual task, and then musically—that is, with all expression that seemed appropriate. In both cases, they were asked to play at the same tempo as in the adjustment task (they could listen to the metronome again) and to take all the time they needed to practice before the recordings.[2]

Note that contrary to the adjustment task, in which timing was the only varying dimension, the pianists could also vary articulation, chord asynchronies, and dynamics (and use the pedals) on the piano. Although they were totally free when playing musically, when playing mechanically, they were asked to maintain other dimensions constant as well and not to use the pedals.

RESULTS

Mechanical Adjustment

Figures 6, 7, and 8 present the average (A) and individual (B) mechanical adjustment timing profiles for the three excerpts. The relative timing variation of each event (the ratio of the adjusted IOI to its nominal value according to the score/tempo) is plotted against its metrical position. If there was no perceptual bias, the points would all fall along a horizontal line (at 1 if the prescribed tempo was followed perfectly). This was not the case, and the results will be examined separately for each excerpt. We expected a perceptual bias to arise from rhythmic grouping, with the last short IOI of rhythmic groups adjusted to be longer than the others. We systematically compared it with the preceding short IOI. This group-final lengthening was expected not to reflect the hierarchy. In addition, for Excerpt 3, we expected a perceptual bias to arise from the intensity differences introduced by the chords, with soft–loud IOIs adjusted to be shorter than loud–soft IOIs.

Excerpt 1. On average, the last short IOI of each rhythmic group was adjusted so as to be longer than the preceding one (filled circles and bold solid lines in Figure 6A; mean difference of 8.4%—i.e., 25 msec). This was observed for all the participants (Figure 6B). An analysis

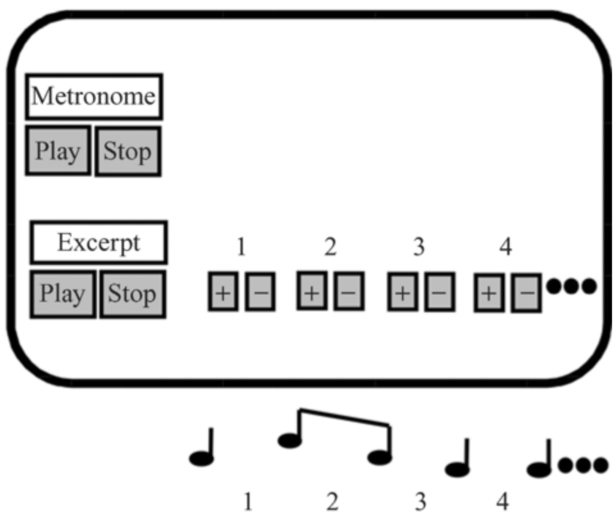

Figure 5. Schema of the computer screen and the score the participants used in the mechanical adjustment task.

of variance (ANOVA) for the relative timing variations, with rhythmic group (5) and position of the IOI in the group (second to last and last short IOI) as factors, confirmed an effect of position [$F(1,4) = 20.4, p < .02$] and revealed no effect of group and no interaction. As was predicted, the last short IOI of each rhythmic group was adjusted so as to be longer than the preceding one in the same way for each rhythmic group—that is, independently of the hierarchy.

Excerpt 2. As is highlighted in Figure 7, this excerpt presents two levels of rhythmic groups: sixteenth-note and eighth-note rhythmic groups. On average, the last short IOI of each sixteenth-note rhythmic group was adjusted so as to be longer than the preceding IOI (filled circles and bold solid lines in Figure 7A; mean difference of 8.0%—i.e., 24 msec), but such a consistent pattern was not observed for eighth-note groups (empty circles and solid lines). These features were also observed at the individual level (Figure 7B) and were confirmed statistically. An ANOVA with sixteenth-note rhythmic group (3) and position of the IOI in the group (2) as factors revealed only an effect of position [$F(1,4) = 9.08$,

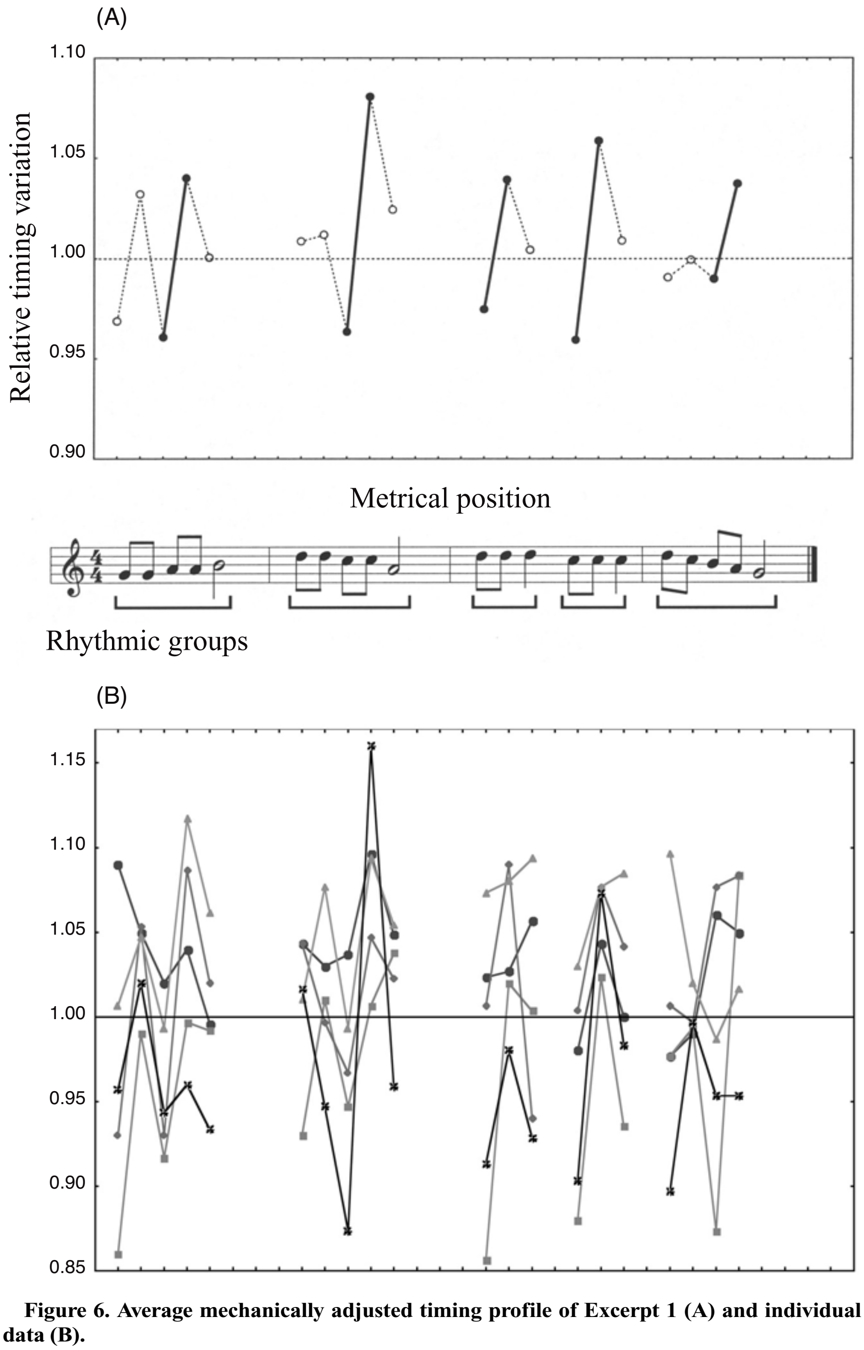

Figure 6. Average mechanically adjusted timing profile of Excerpt 1 (A) and individual data (B).

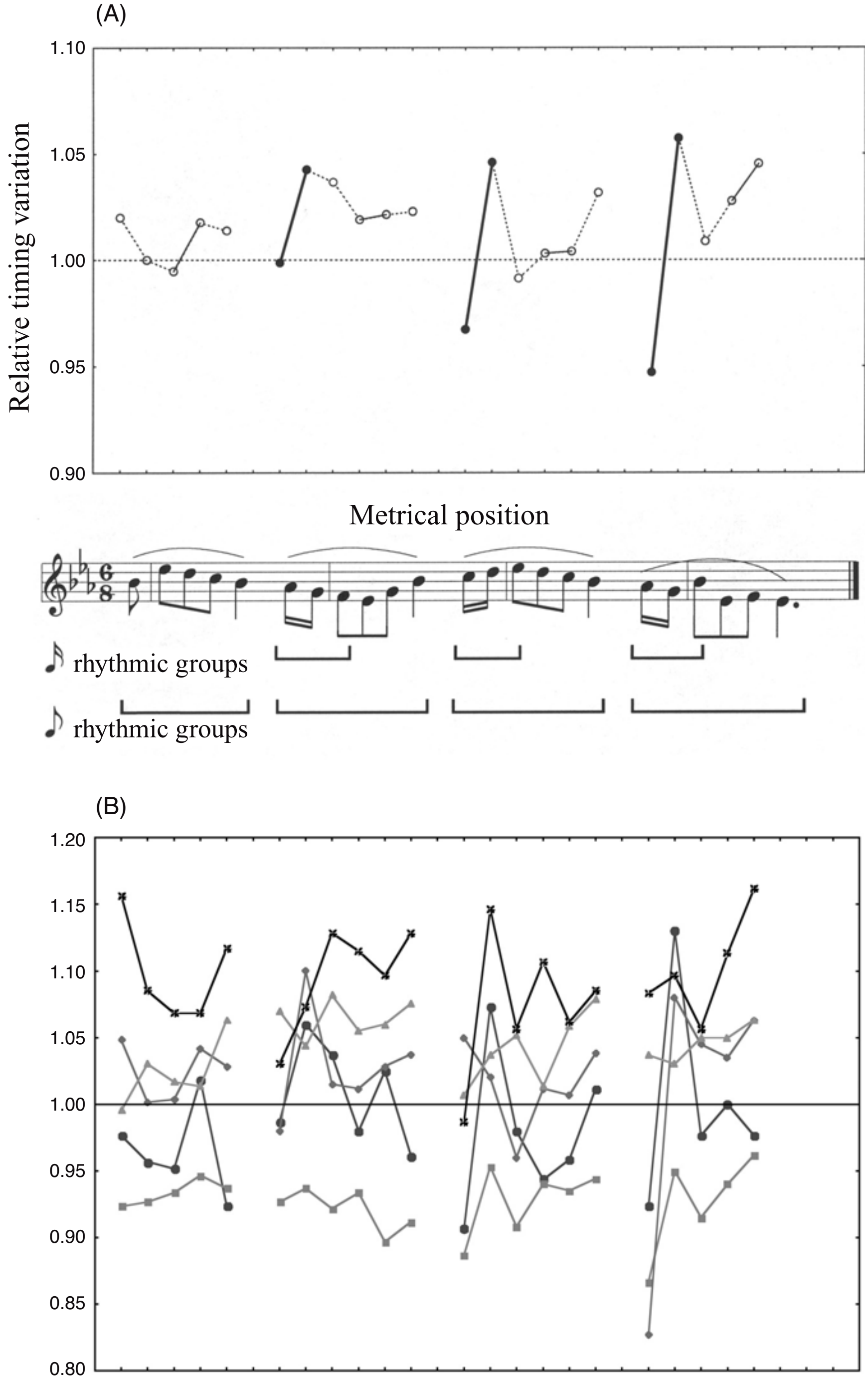

Figure 7. Average mechanically adjusted timing profile of Excerpt 2 (A) and individual data (B).

$p < .04$]. In contrast, the ANOVA for eighth-note rhythmic groups revealed no effect of position. Thus, our predictions were borne out for sixteenth-note rhythmic groups, but not for eighth-note ones: Independently of the hierarchy, the last short IOI of the former was adjusted so as to be longer than the preceding IOI.

Excerpt 3. In addition to the two levels of rhythmic groups, this excerpt exhibits intensity differences between successive events, due to the accompaniment. Some events consist of just one tone, whereas others are chords of between four and six tones (with the exception of the very first event, which comprises two tones). This results in the intensity-based groups indicated in Figure 8. So, in addition to the perceptual bias due to rhythmic grouping (which, according to the results obtained with Excerpt 2, occurs for the sixteenth-note, but not for the eighth-note, groups), we would expect a bias to arise from these intensity differences, with soft–loud IOIs adjusted to be shorter than loud–soft ones, whether the origin of the bias is grouping per se or psychoacoustic (see the introduction). Note that for the intensity-based groups marked by 0, the effects of the two perceptual biases go in opposite directions: The IOI initiated by the single tone should be adjusted to be longer than that initiated by the previous chord because it is the last short IOI of sixteenth-note rhythmic groups, but it should be adjusted to be shorter because it corresponds to a soft–loud IOI versus a loud–soft one. These effects may thus cancel each other. However, in the four other instances, the effect of the intensity differences should be uncontaminated by rhythmic grouping effects.

In this case, the soft–loud IOIs were indeed adjusted to be shorter than the previous loud–soft ones on average (filled circles and bold solid lines in Figure 8A; mean difference of 7.1%—i.e., 43 msec). This was also observed at the individual level (Figure 8B) and was confirmed by an ANOVA with IOI pair (4) and type of IOI (loud–soft and soft–loud) as factors, which revealed an effect of type of IOI [$F(1,4) = 200.25$, $p < .0001$], with no effect of IOI pair and no interaction.

For intensity-based groups marked by 0, for which rhythmic grouping effects conflict with intensity difference effects, no general pattern emerged, as is shown by the average (empty circles and solid lines in Figure 8A) and the individual data (Figure 8B) and as was confirmed by an ANOVA with IOI pair (3) and type of IOI (2) as factors, which revealed no effect of type of IOI. This suggests that the two perceptual biases that we anticipated occurred: one related to sixteenth-note rhythmic grouping and one related to intensity differences.

Mechanical Performance

After the adjustment task, the pianists performed the excerpts on the Disklavier mechanically. Any difference between the mechanically performed profiles and the mechanically adjusted ones will reveal variations due to motor constraints. Given the participants' expertise, we did not expect any, but as was stated before, previous research had suggested that they were possible. As mechanical adjustments, mechanical performances were expected not to reflect the hierarchy. Figures 9A–9C present the average mechanically adjusted and performed profiles, and Figures 9D–9F individual mechanical performances.

Excerpt 1. Figure 9A shows an average mechanically performed profile similar to the mechanically adjusted one ($r = .78$, $p < .001$). In particular, the same variation was observed here: The last short IOI of rhythmic groups was performed so as to be longer than the preceding one. This was true at the individual level (Figure 9D) and was confirmed by an ANOVA with task (2), rhythmic group (5), and position of the IOI (2) as factors, which revealed only an effect of position [$F(1,4) = 32.6$, $p < .01$]. An analysis restricted to the mechanical performances also showed an effect of position only [$F(1,4) = 49.8$, $p < .01$]. As was predicted, there were no additional variations due to motor constraints, and the variations did not reflect the hierarchy.

Excerpt 2. With this excerpt, too, the average mechanically performed profile was similar to the mechanically adjusted one ($r = .78$, $p < .001$; see Figure 9B). The same variation was observed: The last short IOI of a sixteenth-note rhythmic group was performed so as to be longer than the preceding one. This was true at the individual level (Figure 9E), and an ANOVA with task, rhythmic group, and position of the IOI as factors revealed only an effect of position [$F(1,4) = 84.7$, $p < .001$], as did an analysis restricted to the mechanical performances [$F(1,4) = 81.8$, $p < .001$]. Here, too, this variation did not reflect the hierarchy.

In contrast with the mechanical adjustments, however, the lengthening of the last short IOI of eighth-note rhythmic groups, in comparison with the preceding one, was observed here, in the average and in some of the individual data, although the effect was small (1.4%—i.e., 8 msec). An ANOVA with rhythmic group and position of the IOI as factors showed that the effects of position and of group reached significance [$F(1,4) = 10.2$, $p < .04$, and $F(3,12) = 5.15$, $p < .02$, respectively]. Thus, motor constraints did produce some small variations, corresponding to the lengthening of the last short IOI of eighth-note rhythmic groups, but this variation did not reflect the hierarchy.

Excerpt 3. Here, the average mechanically performed profile was quite different from the mechanically adjusted one ($r = .15$, $p < .6$; see Figure 9C). However, it was very similar to the mechanically performed profile of Excerpt 2 ($r = .83$, $p < .001$). It exhibited the same variation as the one observed in the mechanical adjustment and performance of Excerpt 2: The last short IOI of sixteenth-note rhythmic groups was performed so as to be longer than the preceding one. This was observed at the individual level (Figure 9F) and was confirmed by an ANOVA with excerpt, rhythmic group, and position of the IOI as factors, which revealed only an effect of position [$F(1,4) = 53.0$, $p < .01$], as did an ANOVA restricted to the data for Excerpt 3 [$F(1,4) = 22.8$, $p < .01$]. So, the lengthening did not reflect the hierarchy. Either this corresponded to variations due to motor constraints that were exactly opposite to the ones compensating for the intensity differences perceptual bias, or more probably, this bias disappeared. We will return to this in the Discussion section.

As for Excerpt 2, the lengthening of the last short IOI of eighth-note rhythmic groups was observed both in the average and the individual data (5.1%—i.e., 30 msec) and was confirmed by an ANOVA with group and position of the IOI as factors, which revealed only an effect of position [$F(1,4) = 232.7$, $p < .001$]. This again suggests variations due to motor constraints, involving a lengthening of the last short IOI of eighth-note rhythmic groups independently of the excerpt's hierarchy.

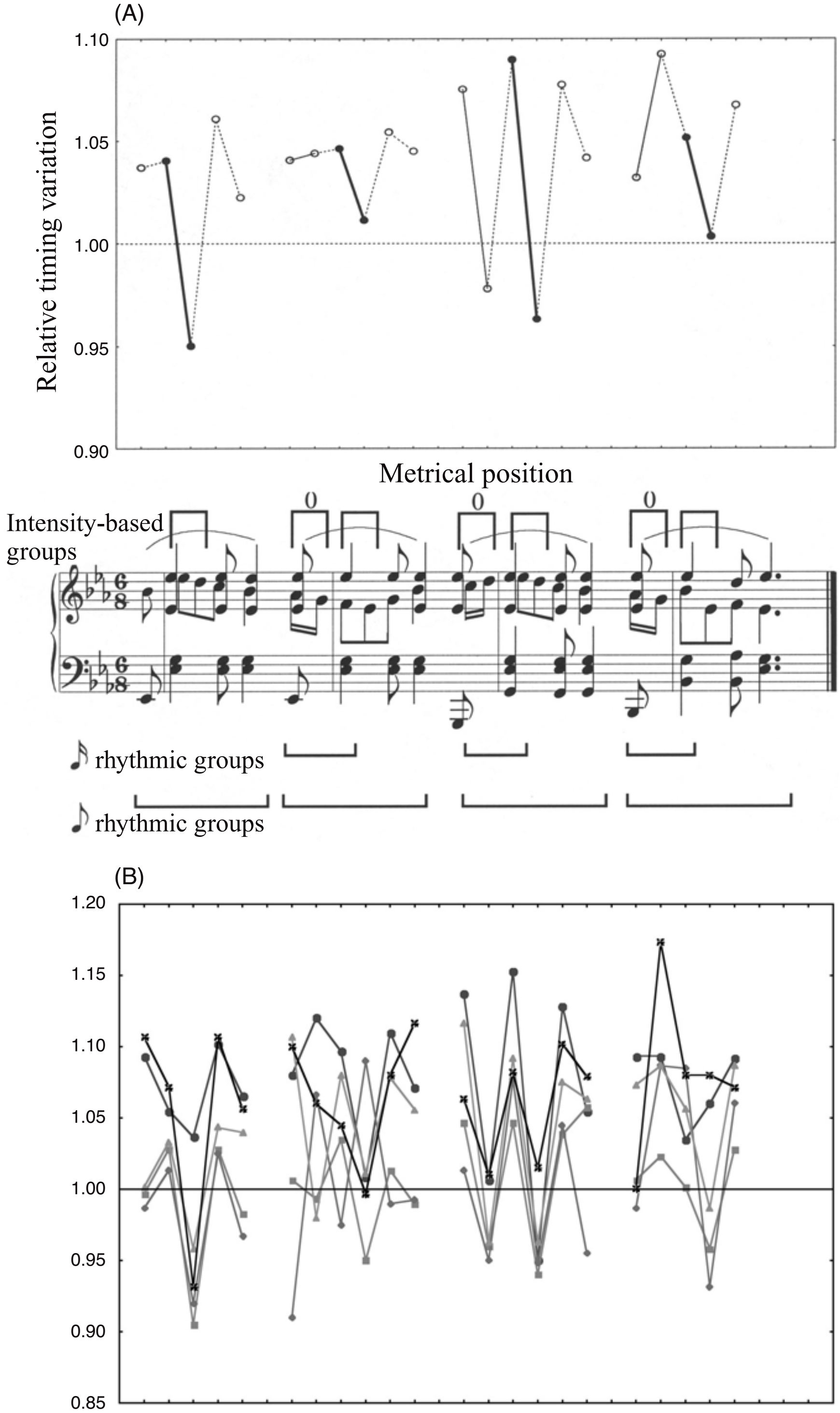

Figure 8. Average mechanically adjusted timing profile of Excerpt 3 (A) and individual data (B).

Musical Performance

Finally, the excerpts were performed musically. The comparison of the musically and the mechanically performed profiles should reveal variations involved in musical communication. We expected greater group-final lengthening, reflecting the hierarchy, due to the communication of the hierarchical grouping structure, and greater variations in Excerpt 3 than in Excerpt 2, due to the enrichment provided by the accompaniment. Figures 10A–10C present the average mechanically and musically per-

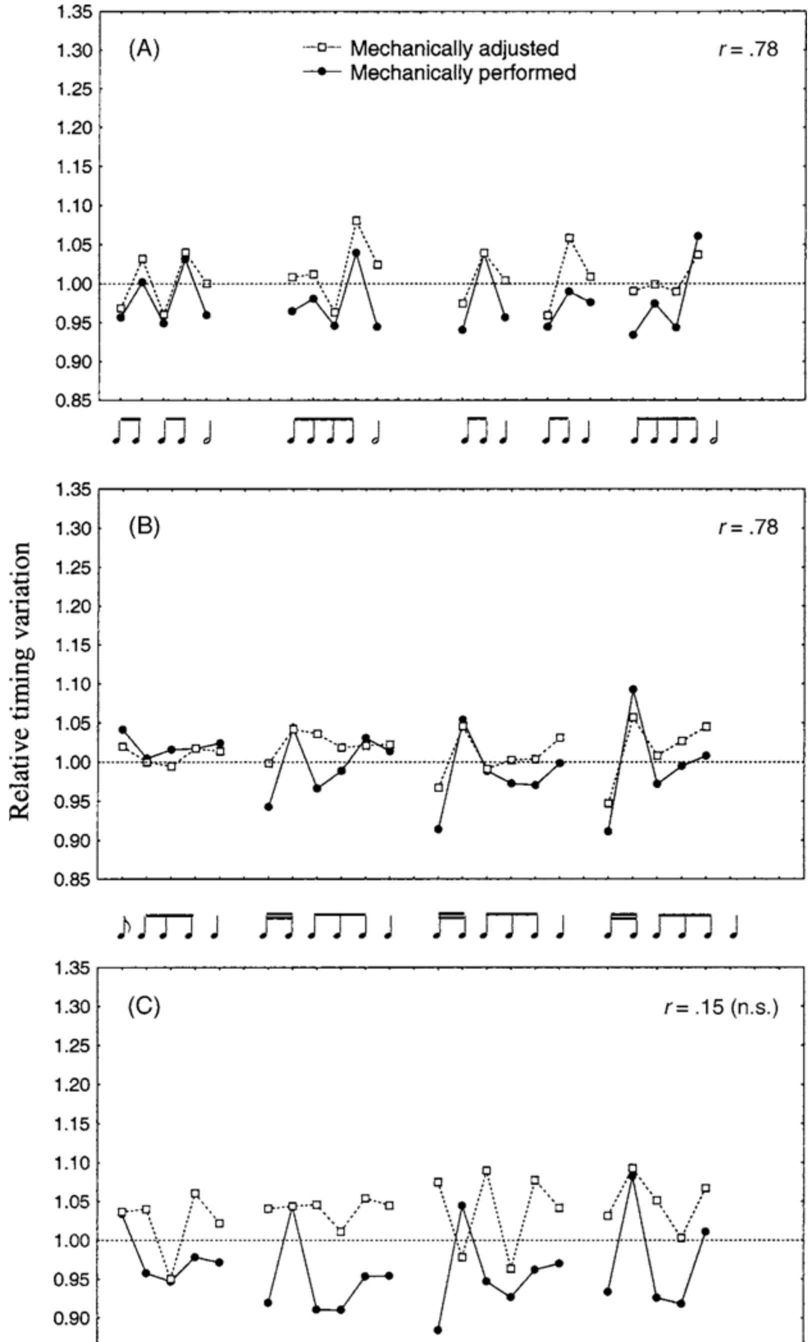

Figure 9. Average mechanically adjusted and mechanically performed timing profiles for Excerpts 1(A), 2(B), and 3(C) and individual mechanically performed profiles for Excerpts 1(D), 2(E), and 3(F).

formed profiles, and Figures 10D–10F present individual musical performances.

Excerpt 1. The average musically performed profile was similar to the mechanically performed one ($r = .80$, $p < .001$; see Figure 10A). In particular, the variation described above was still observed (also at the individual level; see Figure 10D), apparently with a greater amplitude than in mechanical performances for some rhythmic groups. An ANOVA with task, group, and position of the IOI as factors showed effects of group and position [$F(4,16) = 5.81, p < .01$, and $F(1,4) = 22.4, p < .01$, respectively] and an interaction between the two [$F(4,16) = 3.12, p < .05$]. The interaction between task and position was not significant. But taking groups as a random vari-

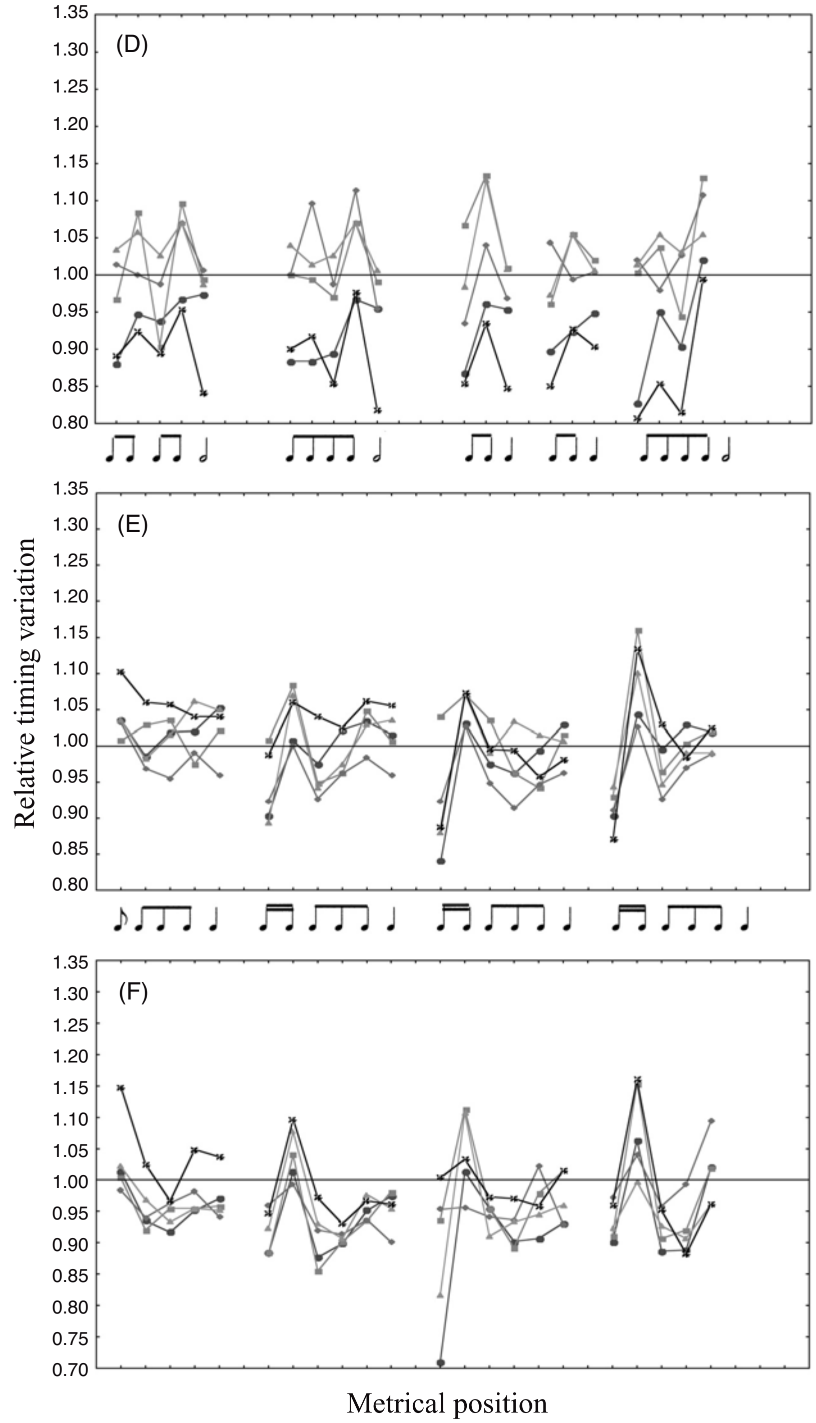

Figure 9. (Continued.)

able and restricting the protocol to Groups 1, 2, and 5 (see Figure 11), it reached significance [$F(1,14) = 6.40$, $p < .03$]. Thus, group-final lengthening was greater in musical performances, in relation to the hierarchy proposed in Figure 11 (Level 2).

An analysis restricted to the musical performances confirmed an effect of position [$F(1,4) = 12.4$, $p < .03$] and also showed an effect of group [$F(4,16) = 4.00$, $p < .02$] and an interaction [$F(4,16) = 3.01$, $p < .05$], which was not observed in the previous tasks. We could not specify it

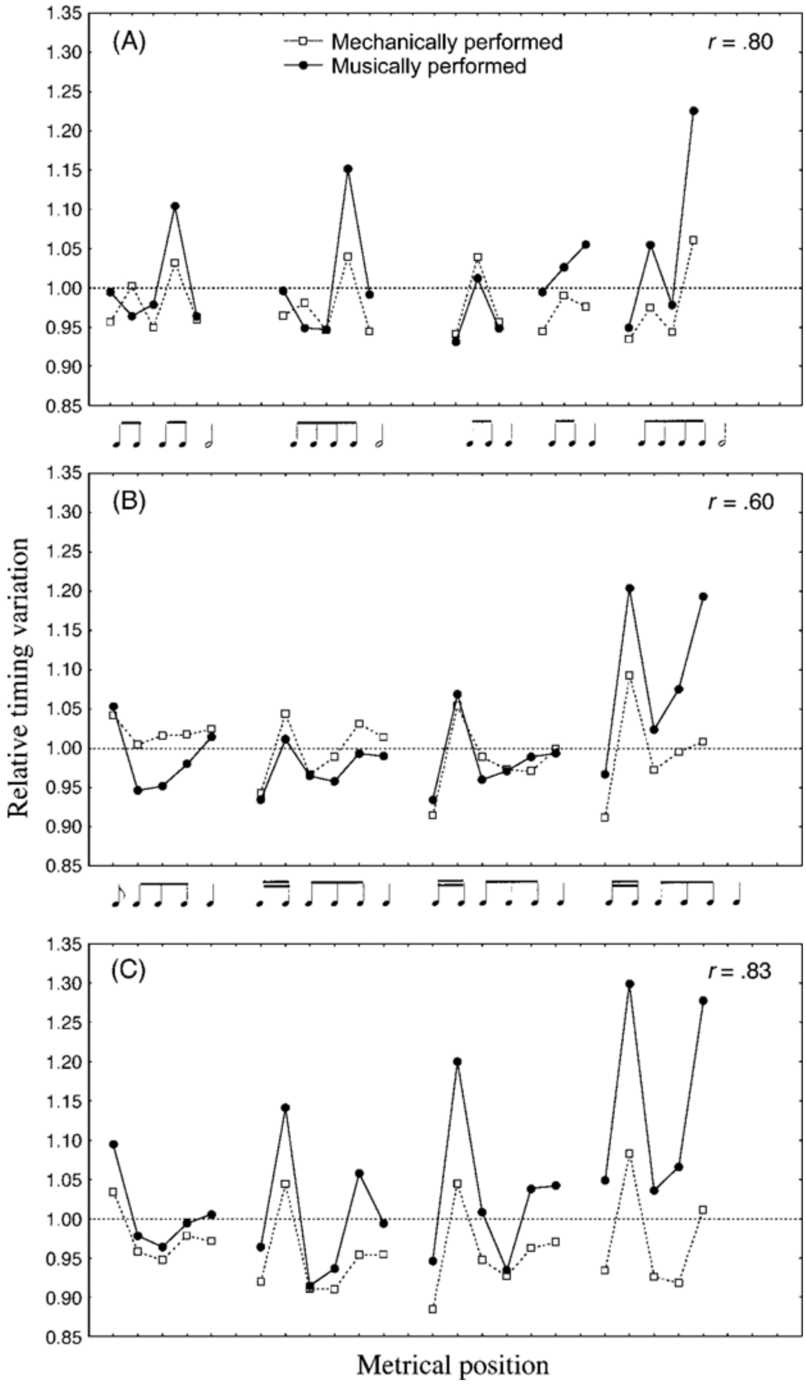

Figure 10. Average mechanically and musically performed timing profiles for Excerpts 1(A), 2(B), and 3(C) and individual musically performed profiles for Excerpts 1(D), 2(E), and 3(F).

with planned comparisons, but the average values suggest that the lengthening was greater for Groups 1, 2, and 5 than for Groups 3 and 4 (Level 2 in Figure 11).

Thus, as was predicted, greater group-final lengthening was observed in musical performances, and it reflected the hierarchy.

Excerpt 2. Here also, the musically and mechanically performed profiles were similar ($r = .60$, $p < .01$; see Figure 10B), with the same variations as those described above for sixteenth- and eighth-note rhythmic groups, which were also observed at the individual level (Figure 10E).

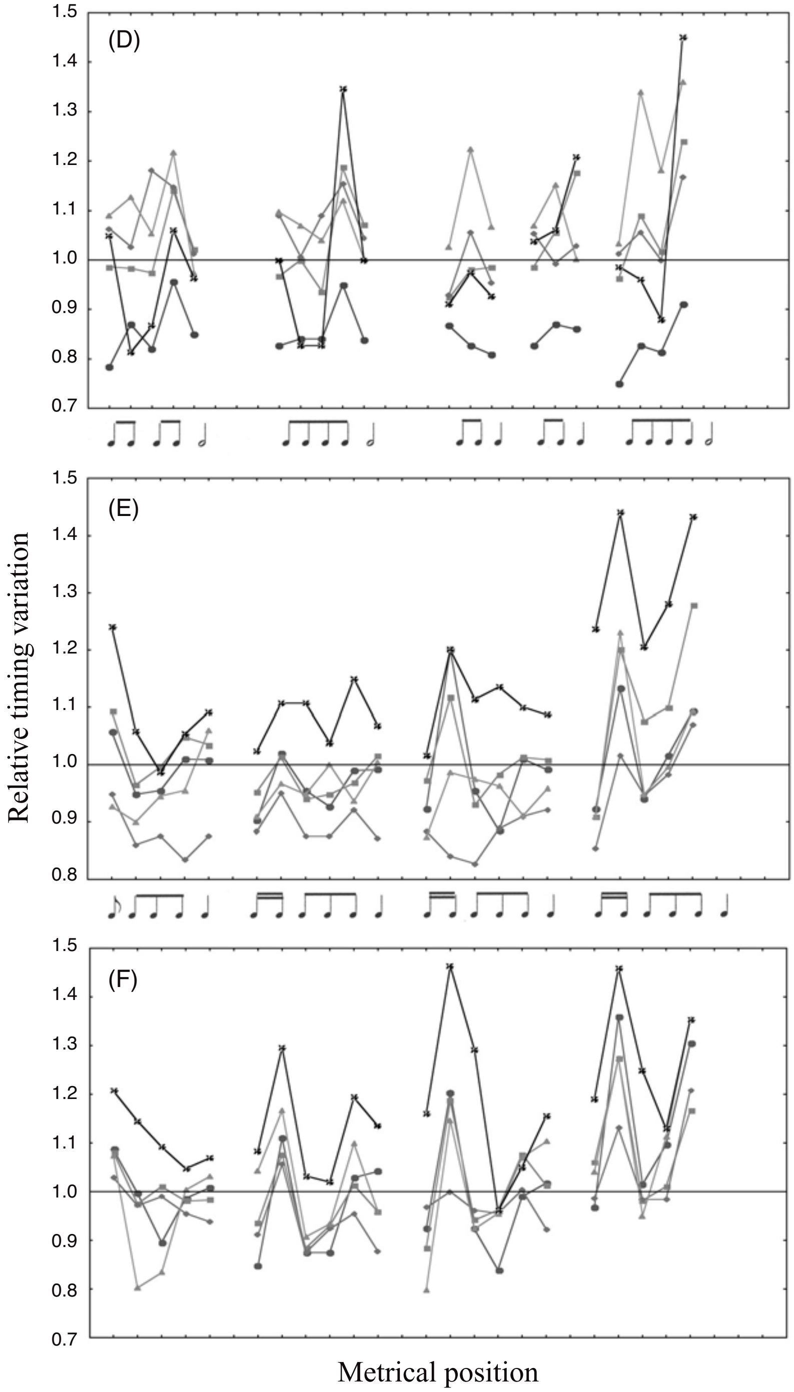

Figure 10. (Continued.)

We first analyzed variations related to sixteenth-note groups. An ANOVA with task, group, and position of the IOI as factors revealed effects of group and position [$F(2,8) = 5.35, p < .04$, and $F(1,4) = 70.7, p < .01$, respectively] and an interaction between the two [$F(2,8) = 7.37, p < .02$], but the interaction between task and position was not significant. This lengthening was not amplified in musical performances. An analysis restricted to musical performances confirmed an effect of position [$F(1,4) = 41.6, p < .01$] and showed an interaction between group and position [$F(2,8) = 6.32, p < .03$], which was not observed in the previous tasks. Planned comparisons revealed that the lengthening was greatest for the third group in relation to the first and second [$F(1,4) = 10.8, p < .03$] and lowest for the first group in relation to the second and third [$F(1,4) = 12.9, p < .03$]. Thus, it in-

Figure 11. Hypothetical interpretation of the Excerpt 1 hierarchical grouping structure by the performers, according to their musical performances.

creased toward the end of the musical phrase and reflected the hierarchy.

In analyzing variations related to eighth-note rhythmic groups, an ANOVA with task, group, and position of the IOI as factors revealed effects of group and position [$F(3,12) = 15.3, p < .001$, and $F(1,4) = 25.6, p < .01$, respectively], an interaction between task and group [$F(3,12) = 10.9, p < .001$], and a triple interaction [$F(3,12) = 3.66, p < .05$]. The interaction between task and position was not significant, and this lengthening was not amplified in musical performances either. An analysis restricted to musical performances confirmed an effect of position [$F(1,4) = 9.91, p < .04$] and revealed an effect of group [$F(3,12) = 14.0, p < .001$] and an interaction [$F(3,12) = 3.99, p < .04$]. This interaction was not observed in mechanical performances. Planned comparisons showed that it was due to a greater effect for the last group than for the three other groups [$F(1,4) = 11.8, p < .03$], which corresponds to phrase-final lengthening.

Thus, for both sixteenth- and eighth-note rhythmic groups, greater group-final lengthening was not observed in musical performances, but it was dependent on the excerpt's hierarchy.

Excerpt 3. Once again, the musically and mechanically performed profiles were similar ($r = .83, p < .001$; see Figure 10C), with the same variations as those described above for sixteenth- and eighth-note rhythmic groups, which were also observed at the individual level (Figure 10F).

In analyzing variations related to sixteenth-note rhythmic groups, an ANOVA with task, group, and position of the IOI as factors revealed effects of task, group, and position [$F(1,4) = 9.87, p < .04$; $F(4,16) = 5.81, p < .01$; and $F(1,4) = 22.4, p < .01$ respectively] and an interaction between task and position [$F(1,4) = 18.5, p < .02$]. This lengthening was greater in musical performances. An analysis restricted to musical performances showed an effect of group [$F(2,8) = 7.49, p < .02$] and confirmed an effect of position [$F(1,4) = 45.2, p < .01$], but the interaction was not significant. Thus, this lengthening did not reflect the excerpt's hierarchy.

We predicted that this lengthening would be greater in Excerpt 3 than in Excerpt 2. An ANOVA with excerpt, group, and position of the IOI as factors revealed effects of excerpt, group, and position [$F(1,4) = 33.4, p < .01$; $F(2,8) = 10.5, p < .01$; and $F(1,4) = 44.6, p < .01$, respectively], with interactions between group and position [$F(2,8) = 5.9, p < .03$] and between excerpt and position [$F(1,4) = 34.6, p < .01$]. Variations related to sixteenth-note rhythmic groups were greater in Excerpt 3.

In analyzing variations related to eighth-note rhythmic groups, an ANOVA with task, group, and position of the IOI as factors revealed effects of task, group, and position [$F(1,4) = 15.3, p < .02$; $F(3,12) = 16.1, p < .001$; and $F(1,4) = 84.6, p < .001$, respectively] and interactions between task and group, group and position, and task and position [$F(3,12) = 10.5, p < .01$; $F(3,12) = 13.7, p < .001$; and $F(1,4) = 8.7, p < .05$, respectively]. Again, a greater lengthening was observed in musical performances. An analysis restricted to musical performances confirmed an effect of position [$F(1,4) = 33.7, p < .01$] and revealed an effect of group [$F(3,12) = 17.1, p < .001$] and an interaction [$F(3,12) = 11.2, p < .001$]. Planned comparisons showed that this interaction was due to a greater lengthening for the last group than for the others [$F(1,4) = 26.8, p < .01$], which again corresponds to phrase-final lengthening.

This variation was, on average, greater in Excerpt 3 than in Excerpt 2, but the effect did not reach significance. An ANOVA with excerpt, group, and position of the IOI as factors revealed only effects of group and position and an interaction between the two [$F(3,12) = 49.6, p < .0001$; $F(1,4) = 57.0, p < .01$; and [$F(3,12) = 10.6, p < .01$, respectively].

Thus, for both sixteenth- and eighth-note rhythmic groups, greater group-final lengthening was observed in musical performances. It reflected the hierarchy for eighth-note rhythmic groups, and for both types of groups it was greater than in the musical performances of Excerpt 2 (however, this reached significance only for sixteenth-note rhythmic groups).

DISCUSSION

The perceptual performance paradigm was designed to explain timing variations in music performance and to distinguish between the perceptual compensation, motor control, and musical communication hypotheses, using three tasks—mechanical adjustment, mechanical performance, and musical performance—the results of which will be discussed in turn.

Mechanical Adjustment

The participants' adjustments of IOIs so that the excerpts sounded regular confirmed two anticipated perceptual biases: one due to rhythmic grouping, with the last short IOI of rhythmic groups being adjusted so as to be longer than the preceding one, suggesting that it was perceived to be shorter, and one due to intensity differences, with a soft–loud IOI adjusted to be shorter than a preceding loud–soft one, suggesting that it was perceived to be longer.

The rhythmic grouping effect was found with Excerpt 1 and with sixteenth-note rhythmic groups in Excerpts 2 and 3, but not with eighth-note rhythmic groups in Excerpt 2 (in Excerpt 3, an eighth-note rhythmic grouping effect would have been confounded with the intensity differences effect and, thus, was not identified). This suggests that the rhythmic grouping perceptual bias does not occur when grouping is not obligatory and that grouping is obligatory for IOIs of 300 msec (as in Excerpt 1 and as for the sixteenth-note groups in Excerpts 2 and 3), but not for IOIs of 600 msec (as for the eighth-note groups in Excerpts 2 and 3). It is indeed known that obligatory grouping decreases as IOI increases (Fraisse, 1956). Fraisse distinguished between "short" and "long time intervals," leading to the "sensation of collection" and that of "duration," respectively, and proposed 400 msec as the limit. Although grouping is possible with longer IOIs, obligatory grouping may occur for IOIs below 400 msec. The perceptual bias identified would then be a witness of the grouping process, as is the gap phenomenon (a loss of time sensitivity between groups; see Fitzgibbons, Pollatsek, & Thomas, 1974; Thorpe & Trehub, 1989). When it occurred, as was predicted, the rhythmic grouping effect was independent of the excerpts' hierarchy.

Why does obligatory grouping result in a bias in time perception? It could be an influence of processing time, with more time being needed toward the end of a perceptual/mnemonic unit to complete its analysis and prepare the storage of new material. Another explanation, stemming from a motor theory of perception, is that we perceive according to common action patterns (e.g., Viviani & Stucchi, 1992). Here, it would mean that because rhythmic groups are usually produced that way, this is how we perceive them as regular. The last short IOI would be lengthened because the production of a rhythmic group consists in a series of movements close in time, followed by a stopping, and it is probably easier to "prepare" the stopping before the last event, via slowing down. An explanation of perception by action has been advanced by Repp (e.g., 1999a, 1999b). However, it seems as plausible to us that perception influences action.

One reviewer has suggested that the effect that we attribute to rhythmic grouping is, in fact, a continuity effect: If an isochronous sequence of tones is followed immediately by a second sequence with IOIs twice as long, the last IOI of the first sequence will need to be lengthened for regularity to be perceived. It is an interesting proposal that may deserve to be investigated further. However, the reasoning should work both ways: If the slow sequence precedes the fast one, the first IOI of the second (fast) sequence will need to be lengthened too. Here, the hypothesis of a *continuity effect* can be rejected on the basis of our data. Indeed, neither was the first eighth-note of rhythmic groups systematically adjusted to be longer than the following one in Excerpt 1, nor was the first sixteenth-note/eighth-note of rhythmic groups in Excerpts 2 and 3 adjusted to be longer/shorter (eighth-note rhythmic groups are preceded by sixteenth-notes). The effect reported is, thus, most likely due to rhythmic grouping.

The perceptual bias related to intensity differences was highlighted with Excerpt 3: Soft–loud IOIs were adjusted so as to be shorter than the preceding loud–soft ones, suggesting that they were perceived to be longer. As was stated in the introduction, this bias has been explained as an effect of intensity-based grouping (Tekman, 1997; Woodrow, 1909; loud tones initiate perceptual groups, and intervals between groups would be perceived to be longer), but a psychoacoustic account is also possible (Tekman, 2001; soft–loud IOIs are perceived to be longer than loud–soft IOIs). At least in our case, we favor a psychoacoustic interpretation: The intensity-based groups are incompatible with the sixteenth-note rhythmic groups (see Figure 8). It seems unlikely that the participants changed their perception of grouping from Excerpt 2 to Excerpt 3. If they had, then *all* the soft–loud IOIs should have been adjusted so as to be shorter than the preceding loud–soft ones. This was not the case, precisely because the intensity effect was combined with an opposite effect of sixteenth-note rhythmic grouping. This shows that the participants retained the perception of grouping they had in Excerpt 2, ruling out the intensity-based grouping hypothesis in favor of a psychoacoustic effect. The precise origin of this psychoacoustic effect also awaits further investigations.

Thus, the baseline against which expressive timing variations are perceived is not the temporal regularity of the score, as has been generally explicitly or implicitly assumed before. Such a perceptual baseline can be provided by a mechanically adjusted profile.

Mechanical Performance

Motor constraints were not predicted to add variations to those compensating for perceptual biases, which again were predicted not to reflect the excerpts' hierarchy. This is what we observed in Excerpt 1 and with the variations related to sixteenth-note rhythmic groups in Excerpt 2. However, in the latter, small additional variations that were independent of the excerpt's hierarchy were found in relation to eighth-note rhythmic groups.

For Excerpt 3, which featured an accompaniment in addition to the Excerpt 2 melody, the mechanical performances differed from the adjustments but were very similar to the mechanical performances of Excerpt 2. This can be interpreted in two ways. First, motor constraints produced variations that were exactly opposite to those compensating for the perceptual bias due to intensity differences. The second interpretation, which we favor, is that this bias disappeared.

Indeed, (1) variations that are due to motor constraints that are exactly opposite to those compensating for the intensity differences perceptual bias seems an improbable coincidence. (2) In addition, informal listening to the excerpt played with IOIs set to their nominal values revealed that, by adopting a global listening strategy, hearing successive tones and chords as if they were the bursts of a metronome, clear hesitations were perceived (IOIs appeared too long) where the intensity differences perceptual bias was measured. In contrast, by adopting a selective listening strategy—that is, focusing on the tones in the melody—these hesitations were no longer perceived. Studies of stream segregation have indicated that the perceived intensity of events is attenuated in nonfocused streams (Botte, Drake, Brochard, & McAdams, 1997). Accordingly, the intensity differences perceived between successive events was reduced in selective versus global listening. The participants probably used a global listening strategy when doing the adjustment task but a selective one when performing on the piano (it has been shown that the melody is a planning unit in production; Palmer & van de Sande, 1993). (3) As the physical intensity differences between successive events were reduced (the performers played the melody louder than the accompaniment note[3]), the perceived intensity differences were reduced all the more.

Thus, although interesting in itself, the perceptual bias due to intensity differences seems to disappear when attention is focused on the melody, which corresponds to natural conditions of music perception and production. In future uses of the paradigm with multivoiced music, it may be useful to ask participants to focus on the melody in the adjustment task and/or to help them to do so by presenting the melody more loudly than the accompaniment.

That the perceptual bias related to intensity differences disappeared in mechanical performances of Excerpt 3 having been established, were there additional variations due to motor constraints with this excerpt? We observed the same variations, related to sixteenth- and eighth-note rhythmic groups, as those for Excerpt 2, which were also independent of the hierarchy. Thus, additional variations due to motor constraints seem to have occurred in relation to eighth-note rhythmic groups. As has been suggested by previous research (Repp, 1999a), motor constraints may produce some variations after all. The ones we found point to a role of rhythmic groups as planning units: More time may be needed toward the end of a group to plan the production of the next one.

Thus, the baseline against which expressive timing variations are performed is not the temporal regularity of the score and can be provided by a mechanically performed profile.

Musical Performances

We predicted that musical communication would produce additional group-final lengthening in relation to the excerpts' hierarchy, with more variations when there was an accompaniment. With some exceptions, these predictions were verified. Greater group-final lengthening in musical performances was found in Excerpt 1 and for both sixteenth- and eighth-note rhythmic groups in Excerpt 3 (but not in Excerpt 2). This reflected the hierarchy in Excerpt 1, for sixteenth-note rhythmic groups in Excerpt 2 (but not in Excerpt 3), and for eighth-note rhythmic groups in both Excerpts 2 and 3. Finally, group-final lengthening was greater in Excerpt 3 than in Excerpt 2 (but the effect did not reach significance for eighth-note rhythmic groups).[4]

CONCLUSION

Rhythmic groups played a central role in the observed timing variations. Chunking is a common process of human cognition (Miller, 1956); it is, thus, not surprising that it constrains music perception and production. In their seminal *Generative Theory of Tonal Music*, Lerdahl and Jackendoff (1983) claimed that "grouping can be viewed as the most basic component of musical understanding." Moreover, they say, "If confronted with a series of elements or a sequence of events, a person spontaneously segments or 'chunks' the elements or events into groups of some kind. The ease or difficulty with which he performs this operation depends on how well the intrinsic organization of the input matches his internal, unconscious principles for constructing groupings" (p. 13). Group-final lengthening seems to be one of these principles.

This study has shown that group-final lengthening, usually attributed to the communication of the grouping structure, is due partly to perceptual constraints (it compensates for a perceptual bias due to obligatory grouping), partly to motor constraints (rhythmic groups may be planning units), and partly to musical communication. Thus, it is necessary for perceptual organization reasons, and listeners are helped in this organization by additional *planning* and *expressive* lengthenings, the latter involving communication of the grouping structure's hierarchy.

The perceptual performance paradigm has potential for future investigations of music performance. Besides being used to examine the generality of the present findings for the timing dimension with other materials, musicians, and instruments, it also could be used to study articulation, intensity, or a combination of these. Also, performers were instructed to adjust IOIs toward *mechanical* renditions. They could be asked to adjust them to produce *musical* performances. In this way, first, even music performance by nonmusicians could be investigated![5] Second, this could provide interesting insights into the problem of the interaction between expressive dimensions. For example, the question could be, which timing variations are necessary when this is the only expressive dimension and which articulation variations can then be added and, conversely, which articulation variations are necessary when this is the only expressive dimension and which timing variations can then be added. If expressive dimensions interact, both timing and articulation variations will be different in both cases.

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NOTES

1. Values were randomly picked from a normal distribution centered around 600 msec, with a standard deviation of 40 msec. To assure perceptual irregularity, values between 560 and 640 msec were excluded. IOIs were derived by multiplying or dividing them, if necessary, according to their nominal values. A new series of IOIs was used for each participant and for each excerpt.

2. The order of tasks was fixed to ensure that the timing variations in perceptual adjustments and mechanical performances would not be contaminated by musical variations and that those in perceptual adjust-

ments would not be contaminated by the interaction with the instrument. We do not think that the order of excerpts (fixed) could have influenced the results.

3. We converted MIDI velocities (1 to 126) into values between 0 and 1. The average melody intensity was higher (.52) than the accompaniment intensity (.44), which was true for all participants and was significant [$t(4) = 8.74$, $p < .001$].

4. Note that the metrical and grouping structures of the excerpts were arranged so that the lengthenings attributed to rhythmic grouping could also be attributed to a lengthening of events preceding metrical accents. However, previous work (Drake, 1993a, 1993b; Drake & Palmer, 1993; Gabrielsson, 1974; Penel & Drake, 1998; Repp, 1992, 1998a, 1998b, 1999a, 1999b) has led us to favor an explanation in terms of rhythmic grouping, rather than metrical accents. The latter can be ruled out, at least for Excerpt 1. With this excerpt and others, Drake and Palmer compared the respective influences of rhythmic groups, melodic groups, and metrical structure on the timing variations produced by making the three structures coincide or conflict. Timing variations related to rhythmic groups were the greatest, pervasive, and still observed when the rhythmic groups were in conflict with both the melodic groups and the metrical structure.

5. However, the methodology would require modifications to remove the reliance on the score.

(Manuscript received September 30, 2002;
revision accepted for publication September 25, 2003.)