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Effects of Auditory Feedback Deprivation on Expressive Piano Performance

BRUNO H. REPP
Haskins Laboratories

Previous studies have suggested that elimination of auditory feedback has no significant effect on the accuracy of keyboard performance. In the present study, this issue was investigated further by focusing specifically on parameters of expression in piano performance: horizontal and vertical timing, horizontal and vertical dynamics, and pedaling. Six pianists performed a short musical excerpt (bars 1–5 of Chopin's Etude in E Major, op. 10, no. 3) 10 times on a digital piano in each of four conditions: expressive with and without feedback, and metronomic with and without feedback. The data analyses revealed significant effects of feedback deprivation on all expressive parameters in both expressive and metronomic performance. However, these effects were very small, except for some substantial changes in pedaling by some pianists. To determine the perceptual and aesthetic significance of these effects, a group of pianist listeners was presented with a forced-choice test in which expressive performances produced with and without feedback were paired with each other. The listeners correctly identified the performance played without feedback on only 63.5% of the trials, which confirms the relative subtlety of the effects of feedback deprivation. Although expression seems to be controlled primarily by an internal representation of the music, auditory feedback may be important in fine-tuning a performance and in the control of pedaling. However, it is also possible that the effects of auditory feedback deprivation merely reflect a lack of motivation to play expressively in the absence of sound.

THE role of sensory feedback in the acquisition and execution of complex motor skills is a topic that has long concerned researchers (see, e.g., Glencross, 1977; Keele, 1968; Rosenbaum, 1991; Summers, 1989). Although it is generally agreed that feedback is most important in the early stages of motor learning, considerable evidence exists that even highly overlearned skills depend on feedback to some extent, especially in their fine-tuning. Referring to a famous study that had shown that deafferented monkeys can still use their limbs for locomotion and grasping (Taub & Berman,

Address correspondence to Bruno H. Repp, Haskins Laboratories, 270 Crown St., New Haven, CT 06511-6695. (e-mail: repp@haskins.yale.edu)

1968), Rosenbaum (1991) notes that "much of the grace and subtlety that is present when feedback is available deteriorates when feedback is withdrawn" (p. 108). Grace and subtlety are two qualities that are essential for the aesthetic quality of movement, as in human dance and music performance. One may therefore surmise that sensory feedback is important even to expert performers in these domains. However, surgical deafferentation is not a viable research technique for addressing this hypothesis.

Most motor activities provide multiple sources of sensory feedback. For example, piano performance—the topic of this study—provides kinesthetic, tactile, visual, and auditory information to the player. Of these, visual feedback is perhaps the least important and certainly the easiest to eliminate: It is sufficient to close one's eyes or to gaze heavenward, as indeed some pianists do occasionally during performance. Moreover, there are blind keyboard players of high accomplishment. Although no studies of fluent piano performance under conditions of visual feedback deprivation seem to have been published, it is a fair guess that visual guidance is important mainly when starting to play and when executing leaps (Lee, 1989) or other large displacements of hand position (cf. Glencross & Barrett, 1983). In a sight-reading task, Banton (1995) found a significant increase in errors when pianists were prevented from looking at their hands.

Tactile feedback may be somewhat more important, although its role has not been investigated. One could imagine that anesthetizing a pianist's fingertips would interfere somewhat with subtlety of touch and fluency of execution, but the impairment would probably not be serious. By contrast, kinesthetic feedback is almost certainly of crucial importance. A pianist who suddenly lost all afferent information from his or her arms and hands would surely be seriously handicapped, even though labored playing might still be possible under visual and auditory guidance. The author is not aware of any studies of keyboard players with deafferentation due to spinal or cortical injury. Presumably, even if such cases existed, the impairment would be too obvious (and tragic) to warrant detailed study.

This leaves auditory feedback. At first glance, audition would seem to be the most important sensory modality in music performance. After all, the only purpose of carrying out amazingly precise and complex motor actions on an instrument is to produce sonic consequences that give aesthetic satisfaction to the player and other listeners. Therefore, one might think that, without sensory information about the sounds produced, keyboard performance would disintegrate. However, this is not so, as several studies (reviewed below) have shown. The reason is that musicians rely on an internal representation (a mental image) of the music to guide and pace their performance, even in the absence of any audible sound. This ability is part of what Gordon (1993) has called "audiation," or what others might call musical thought or imagery. According to Gordon, "an instrument is simply an extension of the audiation of the person who uses it" (p. 41).

To be sure, comparably detailed performance plans underlie other complex, highly practiced motor skills and may protect them from disintegration when feedback is selectively removed. For example, writing with closed eyes is a situation not unlike playing an instrument without sound, and it certainly can be done without much difficulty, although certain characteristic errors such as extra strokes may be observed (Smyth & Silvers, 1987). However, I am not aware of any study that specifically addressed the question of whether the aesthetic quality of the resulting handwriting is reduced. An even more relevant task is speech production without auditory feedback. A methodological problem here is that one cannot simply turn a speaker's voice off; it is necessary to either introduce loud masking noise over earphones or to study individuals who have suddenly lost their hearing. Speech production in loud noise typically exhibits the "Lombard sign" (an involuntary raising of the vocal level) as well as subtle changes in articulation designed to maintain or enhance intelligibility (Lane & Tranel, 1971). Studies of postlingually deafened individuals have generally been focused on long-term rather than immediate effects. Nevertheless, it is of interest that impairments in both segmental and suprasegmental articulation have been observed, particularly in those suprasegmental aspects that are not governed by linguistic rules, such as fine control of pitch and timing (Waldstein, 1990).

The effect of removing auditory feedback on keyboard performance has been investigated in a few studies. Until recently, however, such research was methodologically difficult and analytically crude. Nevertheless, as long as one century ago, Ebhardt (1898) succeeded in largely eliminating auditory feedback by physically separating a piano's keyboard and action from its strings. When four pianists played the same pieces with and without sound, they were found to play consistently slower in the silent condition.[1] No other impairment was noted by Ebhardt, which is not surprising because he could not hear the silent performances. With the advent of electronic instruments, it became possible to simply switch off the sound or unplug the earphones. Thus, Gates and Bradshaw (1974) asked six musicians to rehearse and play an etude on an electronic organ with and without sound. Again, they measured only the overall duration of the performances. In contrast to Ebhardt, they did not find a significant difference, only a nonsignificant tendency in the same direction.

1. Clynes and Walker (1982) found a similar tempo difference when comparing actual with imagined music performances. A nonsignificant tendency in the same direction was observed by Gabrielsson and Lindström (1995) with simpler materials that were either played on a synthesizer or tapped out on a sentograph.

More recently, MIDI technology has made it possible to record, analyze, and even play back keyboard performances that were originally played without sound. Banton (1995) took some limited advantage of these possibilities in her study of sight-reading accuracy but did not find any significant increase in errors when auditory feedback was removed (in contrast to her results for visual feedback deprivation). A far more detailed study of the effects of auditory feedback deprivation on keyboard performance was conducted by Finney (1997). Eleven pianists of various skill levels played parts of two Bach two-part inventions on an electronic keyboard with and without sound. Finney found no significant differences between the normal and silent conditions with regard to number of errors, overall tempo, overall dynamic level (average key-press velocity), between-hand asynchrony, variability of note durations, and variability of note interonset intervals. In a subsequent perceptual judgment task, three judges rated performances that had been played without auditory feedback as being worse than normal performances 62% of the time; apparently, this result was not significantly different from chance (50%).[2]

Thus, the studies conducted so far do not reveal any consistent effects of auditory feedback deprivation on keyboard performance. However, none of these studies was concerned with expression, where the "grace and subtlety" that Rosenbaum (1991) was referring to is found. Although Finney (1997) examined performance parameters that are important to musical expression, he had chosen music that did not invite much expression and moreover had explicitly instructed the participating pianists to play "at an even tempo without expressive variation" (p. 159). His main concern was the effect of delayed or altered auditory feedback on the accuracy of performance (as in the study of Gates & Bradshaw, 1974). Distorted and misleading feedback clearly has a disruptive effect on music performance, as it does on speaking (see, e.g., Fairbanks, 1955), and this clearly demonstrates that auditory input is not ignored entirely. However, these findings are not pertinent to the present study, which is solely concerned with the effects of substituting silence for auditory feedback.

Is normal auditory feedback then really redundant in playing a keyboard instrument? Can piano performance in all its expressive detail be guided by an internal representation or mental image of the musical sound structure alone? This is in essence a question about the richness of the internal representation. Performance without sound obviously is not of any interest in itself. Rather, it is an experimental probe into the musical thought of the performer. If silent performance is identical to sonic performance, then this implies that every performance detail has been prespecified, so that the

2. These perceptual judgment results were reported in an earlier draft of Finney's article but were not included in the published version.

(solo) performance is entirely an open-loop (feed-forward) process. Whether this is true may depend on a number of factors, including the complexity of the music, the experience of the performer, and the amount of specific rehearsal. No attempt was made here to vary these factors systematically. Rather, only one particular constellation of factors was examined, in a first attempt to investigate the effects of auditory feedback deprivation on truly expressive piano performance.

A musical passage was selected that requires fine control over expressive timing, dynamics, texture, and pedaling. Although it was relatively short and slow in tempo, it was of sufficient complexity to provide a stringent test of the null hypothesis that auditory feedback deprivation has no effect whatsoever. In addition to the auditory feedback manipulation, pianists were instructed to play the music either expressively or metronomically (i.e., in strict time, but without the aid of a metronome). This made it possible to distinguish effects of auditory feedback deprivation that occur in both conditions from effects (if any) that are specific to expressively timed performance. Although the primary effect of metronomic playing was obviously on expressive timing, secondary effects on other performance parameters and their potential interactions with the feedback manipulation were also of interest.

As will be seen, the pianists in this study were highly skilled, but not supreme masters of their instrument. The practice provided was limited and the instrument unfamiliar, which led to performances that were not perfect in every respect. In other words, the internal representations and motor programs required for the task were not solidly established, which probably made them more vulnerable to auditory feedback deprivation. This was not considered a shortcoming, especially in view of the negative results of previous studies. The aim was to examine whether eliminating auditory feedback *can* make a difference under these particular conditions. Once significant effects have been demonstrated, then one may ask whether increased practice or expertise would make them go away. This seemed a better research strategy than to start at the highest level of expertise, where the effects are likely to be smallest.

The data analyzed here in depth derive from a previous study of timing control in pianists that, in addition to the four conditions mentioned, included eight additional tasks (Repp, in press-a). The analyses in that study dealt only with a single performance parameter, "horizontal" timing (i.e., the timing of successive note onsets), and it focused strongly on individual differences. These timing data are reanalyzed here, for the four conditions of interest, with a focus on group results. In addition, analyses of four other performance parameters are presented: horizontal dynamics (the relative intensities of successive notes), vertical timing (the asynchronies among nominally simultaneous notes), vertical dynamics (the relative intensities of nominally simultaneous notes), and pedaling. This list nearly exhausts the quantifiable parameters of piano performance. Only articulation (gaps and overlaps among successive notes) was not examined, as it had hardly any audible consequences in the musical excerpt selected, owing to almost continuous use of the sustaining pedal.

Pedaling was of special interest, for two reasons. First, the pedal is out of the pianist's sight and also arguably provides less kinesthetic and tactile feedback than do manual actions. Therefore, pedaling may depend more heavily on auditory feedback. Indeed, in the pedagogical literature, the point is often made that pedaling is "governed by the ear" (e.g., Banowetz, 1985, p. 9; Neuhaus, 1973, p. 162). Second, pedaling is under less conscious control than are actions on the keyboard, on which the player's attention is typically focused. Heinlein (1930) found that accurate pedaling is difficult in a variety of conditions different from normal performance, such as imagining the music, tapping the melody on a silent key, singing the melody, playing the melody on the keyboard with a single finger, and listening to a recorded performance. Heinlein concluded that "[t]he damper-pedal response is so highly integrated into a unity of effect with the other phases of a pianoforte performance that alteration of any single factor or group of factors ... may seriously modify a pianist's customary pedal interpretation" (p. 527). The present study examined to what extent this may hold when only auditory feedback is removed, with all other aspects of normal performance being preserved. Moreover, the analyses of pedaling focused not only on pedal use (Heinlein's "pedal interpretation") but also on pedal timing (cf. Repp, 1996a, 1997c).

Each performance parameter (except for pedal use) was measured as a function of metrical position in the musical score for 10 successive performances in each playing condition. For each of these parameters, auditory feedback deprivation could have consequences of three kinds: (1) an increase in within-condition variability (across performances); (2) a main effect, such as a slower tempo or higher dynamic level overall; (3) a differential effect across the metrical positions—that is, an interaction of feedback with metrical position.

The performance analysis was followed by a perceptual experiment that tested pianists' ability to distinguish expressive performances played with and without feedback, in order to determine the aesthetic significance of the differences uncovered in the performance analysis. It was assumed that these differences (if any) would not be in favor of the silent performances. In other words, it was considered highly unlikely that performances would improve in the absence of auditory feedback, even though the order of conditions was biased in that direction (see below). However, it was understood that not every difference necessarily has an aesthetic impact.

Performance Analysis

METHOD

The Music

The musical excerpt used was the beginning of Chopin's Etude in E Major, op. 10, no. 3, a beautiful and well-known composition that requires fine control over all aspects of expression. A computer-generated score, without slurs and expression marks, is shown in Figure 1. The excerpt was terminated here with a sustained chord, omitting the continuing sixteenth-note motion of the original. The music is essentially in four parts or voices. The melody in the soprano voice is divided into several rhythmic groups, each ending with a long note, as indicated by the brackets above the score. The alto voice accompaniment is a continuous sequence of sixteenth notes. The tenor voice establishes a syncopated rhythm, and the bass underlines the harmonic alternation of tonic and dominant. Additional notes between the soprano and alto voices mainly serve to enrich the harmony and are labeled "mezzo" (short for mezzo-soprano) in some of the analyses described here.[3] Following the initial eighth-note upbeat, the music contains 36 nominally equal interonset intervals (IOIs) corresponding to sixteenth notes, as indicated below the score. Analyses of horizontal timing and horizontal dynamics will make reference to "primary notes", which were defined as the highest-pitched notes in all metrical (sixteenth-note) positions of the music (i.e., all soprano notes and those mezzo or alto notes that occur during sustained soprano notes). These notes may be reasonably assumed to be more salient, both to the pianist and to a listener, than any lower-pitched notes that coincide with them.

Participants

Six pianists participated. One of them was the author (B. R.), an advanced amateur who had been playing informally but regularly for 47 years. The others were young musicians

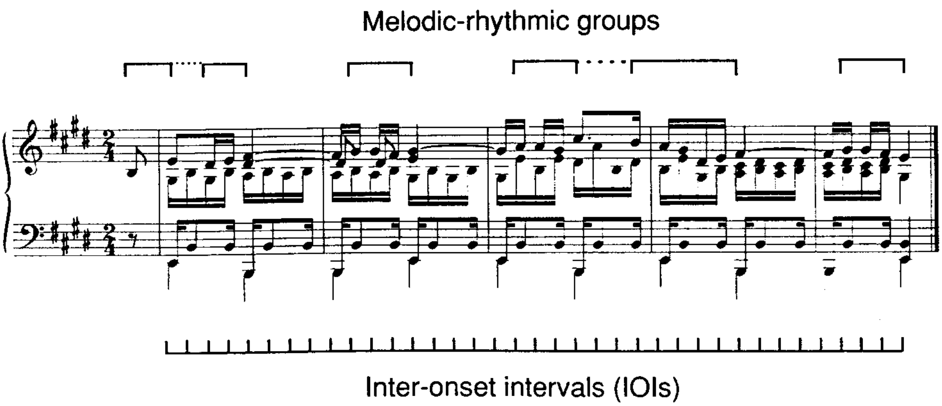

Fig. 1. The opening of Chopin's Etude in E Major, op. 10, no. 3., as used in the present study.

3. The "mezzo" notes are the D♯ in position 1-5 (bar number followed by sixteenth-note number), the D♯ in position 2-3, the E in position 2-5, and the upper notes of the parallel thirds in positions 4-5 through 5-4.

with professional training: one with a master's degree in piano performance from the Yale School of Music (D. G.), two graduate students in the same program (T. C., H. S.), and two of the best undergraduate pianists at Yale University, a senior (K. S., who entered the graduate piano program the following year) and a sophomore (M. S.). They had been practicing the piano intensively for 15–20 years.

Procedure

The instrument was a Roland RD-250s digital piano equipped with a simple pedal switch.[4] After a brief warm-up, each participant performed the Chopin excerpt 10 times from the score (as shown in Figure 1, but without the annotations), playing with the best expression he or she could muster, without changing the interpretation in successive performances. Auditory feedback was provided over Sennheiser HD 540 II earphones using the "Piano 1" sound of the digital piano. Subsequently, the earphones were removed and disconnected, and the pianist played the excerpt another 10 times, trying to reproduce the previous interpretation as closely as possible. Four other experimental conditions followed that involved finger tapping rather than keyboard performance (see Repp, in press-a). About half an hour later, the pianist returned to the digital piano and again played the Chopin excerpt 10 times with auditory feedback and 10 times without. However, he or she was instructed to play these performances metronomically, that is, in strict time, but without the aid of a metronome. The four playing conditions will be referred to as EF+ (expressive with feedback), EF– (expressive without feedback), MF+ (metronomic with feedback), and MF– (metronomic without feedback), respectively. In the statistical analyses, the E/M dimension will be referred to as *task* and the F+/F– dimension as *feedback*.

None of the pianists had recently practiced the Chopin etude; in fact, four of them had not played it previously and knew it only from listening. The performances thus were not extensively rehearsed, and this was thought to make them more vulnerable to possible effects of feedback deprivation. Performances were recorded in MIDI format by a Macintosh Quadra 660AV computer with MAX software.[5] The data were saved in text format and analyzed with a spreadsheet program as well as standard statistical procedures.

RESULTS AND DISCUSSION

Horizontal Timing

Horizontal timing refers to the sequence of IOI durations between successive primary notes, as defined earlier. (A selection of reference notes is necessary because nominally simultaneous note onsets are not exactly synchronous; see the analysis of "vertical timing" that follows.) The initial eighth-note upbeat was ignored, so that all 36 IOIs in the excerpt were nominally equal (i.e., sixteenth-note intervals). The variation in IOI duration as a function of metrical position constitutes the *timing profile* of the music. Although the timing results have been reported previously (Repp, in press-a), they are described in a different format here. The earlier graphs and statistical analyses focused on individual pianists, whereas here grand

4. The pedal switch produced a mechanical noise that was largely masked by the music in the tasks with feedback but was more clearly audible to the pianist in the tasks with no feedback. The primitive nature of this device is a shortcoming of the present study.

5. Measurements of MAX input and output have shown that its internal representation of time (in the particular computer configuration used) is about 2.4% slower than real time. No correction was applied to the timing data, as absolute tempi were of little interest.

averages and combined statistical analyses of all six pianists are presented. Throughout this paper, only statistical results of primary interest will be reported, in order to avoid information overload.

Figure 2 shows the timing profiles in the four playing conditions, averaged across all six pianists. (The profiles were quite similar among the six pianists, although there were individual differences in basic tempo and de-

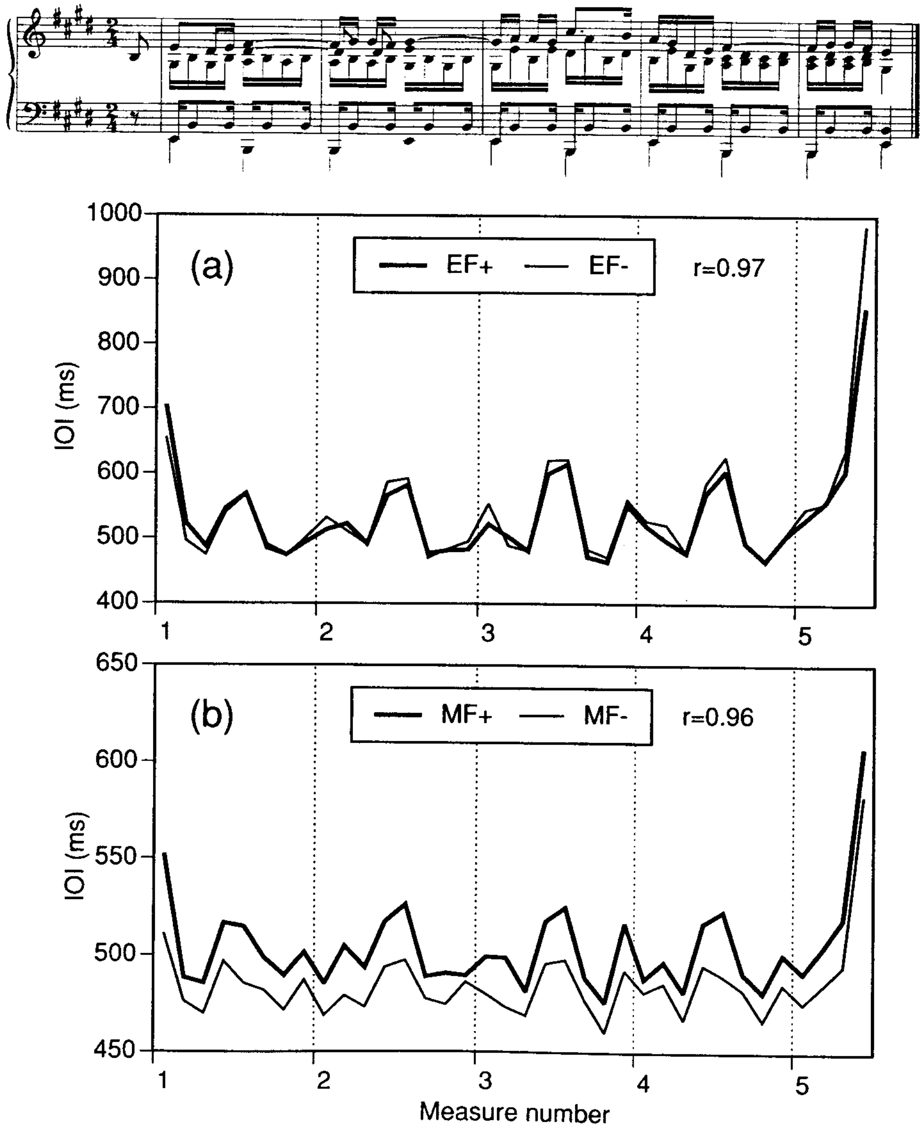

Fig. 2. The average expressive timing profiles in four playing conditions: expressive with and without auditory feedback (EF+, EF–), and metronomic with and without auditory feedback (MF+, MF–). IOI = interonset interval.

gree of timing modulation.) The two expressive tasks are shown in the upper panel and the two metronomic tasks in the lower panel; the score is shown above the figure for guidance. There are eight data points (sixteenth-note positions) per bar, corresponding to slope changes in the functions; symbols have been omitted to avoid clutter. The different scales on the y-axes of the two panels should be noted.

One interesting finding was that there were systematic timing variations in metronomic performance (Figure 2b) that greatly resembled the much larger variations in expressive performance (Figure 2a). For discussion of this result, see Repp (in press-a), and for related findings, see Palmer (1989), Penel and Drake (1998), and Repp (in press-b). Here the focus is on the effects of auditory feedback. It is evident that the timing profiles in the F+ and F– conditions were very similar in both tasks; the correlation coefficients are shown in the figure. Nevertheless, statistical analysis revealed significant differences. A three-way repeated-measures analysis of variance (ANOVA) with the variables task (2 levels), feedback (2 levels), and position (36 levels) revealed a highly significant three-way interaction, $F(35, 175) = 6.53$, $p < .0001$. Separate two-way ANOVAs on the expressive and metronomic profiles showed the Feedback × Position interaction to be significant in each case, $F(35, 175) = 4.53$, $p < .0001$, and 1.90, $p < .004$, respectively. In the expressive condition (Figure 2a), the final IOI was lengthened considerably when feedback was absent; in other words, the pianists made a greater final ritard. However, this was not the only difference: When the two-way ANOVA was redone with the final IOI omitted, the Feedback × Position interaction remained highly significant, $F(34, 170) = 2.99$, $p < .0001$. It seems that expressive lengthening at the ends of melodic groups (in the middle of each measure) was generally somewhat greater when feedback was not available. In the metronomic task (Figure 2b), there seems to be a tendency in the opposite direction, which may be responsible for the significant interaction. The basic tempo appears to be slightly faster in the MF– than in the MF+ condition (contrary to the findings of Ebhardt, 1898), but the main effect of feedback was nonsignificant in both tasks.

Figure 3 shows the average within-condition standard deviations of the 36 IOIs (i.e., their variability across the 10 performances in each of the four conditions, computed separately for each pianist and then averaged across pianists) as a function of their average durations, with regression lines. It is evident that IOI variability increased with IOI duration, a finding reported and discussed previously (Repp, 1997b, in press-a). This relationship was apparent even in the metronomic tasks, where the range of IOI durations was quite narrow, and it was reflected in highly significant main effects of position in ANOVAs on the standard deviations. The large variability of the long final IOI clearly made a major contribution. With this IOI omitted, the main effect of position remained highly significant in

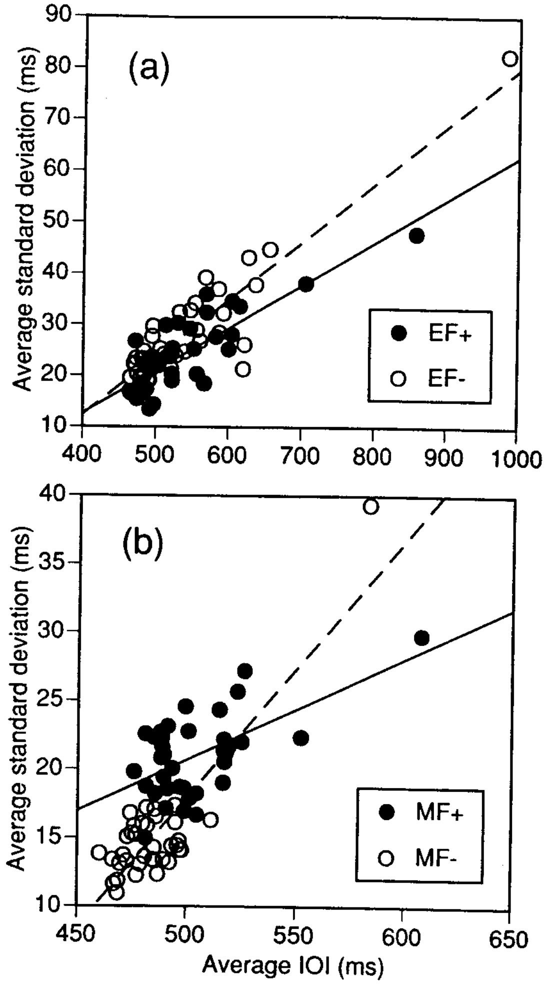

Fig. 3. The relationship between average duration of the interonset interval and average variability across performances in the four playing conditions, with regression lines. EF+ = expressive with auditory feedback, EF– = expressive without auditory feedback, MF+ =metronomic with auditory feedback, MF– = metronomic without auditory feedback.

the two-way ANOVA on the expressive tasks, $F(34, 170) = 3.47, p < .0001$, but it fell short of significance in the metronomic tasks, $F(34, 170) = 1.47$, $p < .06$.

Even though Figure 3 suggests opposite effects of feedback on variability in the two tasks, the Task × Feedback interaction was not significant in the three-way ANOVA. In separate ANOVAs on the two tasks, the main effect of feedback reached significance only in the expressive tasks, $F(1, 5) = 13.16$, $p < .02$, indicating somewhat greater variability when feedback was absent.

In summary, neither intended nor unintended horizontal timing depended crucially on auditory feedback. However, the statistical results suggest that auditory feedback deprivation had subtle effects on timing. It is possible, however, that these changes represent effects of practice, since the F– conditions followed the F+ conditions: The expressive performances became slightly more expressive and the metronomic performances slightly more metronomic. In addition, variability of expressive timing was somewhat greater in the absence of feedback, but this could be related to the increased temporal modulation.

Horizontal Dynamics

Horizontal dynamics refers to the relative intensities of successive primary notes, as defined in the Method section. The measure of relative intensity was MIDI velocity, a numerical scale (0–127) reflecting the relative velocities of key depressions on the digital piano. The acoustic intensity (peak sound level in decibels) of the piano tones is a monotonic but nonlinear (negatively accelerated quadratic) function of MIDI velocity (see Figure 1 of Repp, 1997a). The variation in primary-note velocity as a function of metrical position constitutes the *dynamic profile* of the music.

The average dynamic profiles for the four playing conditions are shown in Figure 4. Their peaks correspond to soprano melody notes, their valleys to mezzo or alto accompaniment notes during sustained melody notes. (The profiles were highly similar among the six pianists, although individual differences in dynamic range were apparent.) The dynamic profiles for the expressive and metronomic playing tasks were highly similar in shape (r = .984 with feedback, r = .974 without), but the dynamic range was clearly reduced in the metronomic condition, mainly because of a raised dynamic level of the accompaniment. This difference was reflected in a significant main effect of task, $F(1, 5) = 23.51$, $p < .005$, and a significant Task × Position interaction, $F(36,180) = 7.68$, $p < .0001$, in the three-way ANOVA. The profiles in the F+ and F– conditions were extremely similar; the correlations are shown in the figure. Nevertheless, Task × Feedback and Position × Feedback interactions were significant, $F(1, 5) = 23.96$, $p < .005$; $F(36, 180) = 3.48$, $p < .0001$, but there was no triple interaction. Separate two-way ANOVAs revealed a significant main effect of feedback only in the metronomic task, $F(1, 5) = 25.09$, $p < .005$: The average dynamic level was somewhat higher when feedback was absent, as can be seen in Figure 4b. However, the Position × Feedback interaction was significant in both tasks, $F(36, 180) = 2.41$, $p < .0002$, and 2.60, $p < .0001$, respectively, which indicates subtle changes in the shape of the dynamic profile as a consequence of feedback deprivation. Figure 4 suggests that these changes amount to a slight reduction of dynamic range in the absence of auditory feedback, in both tasks.

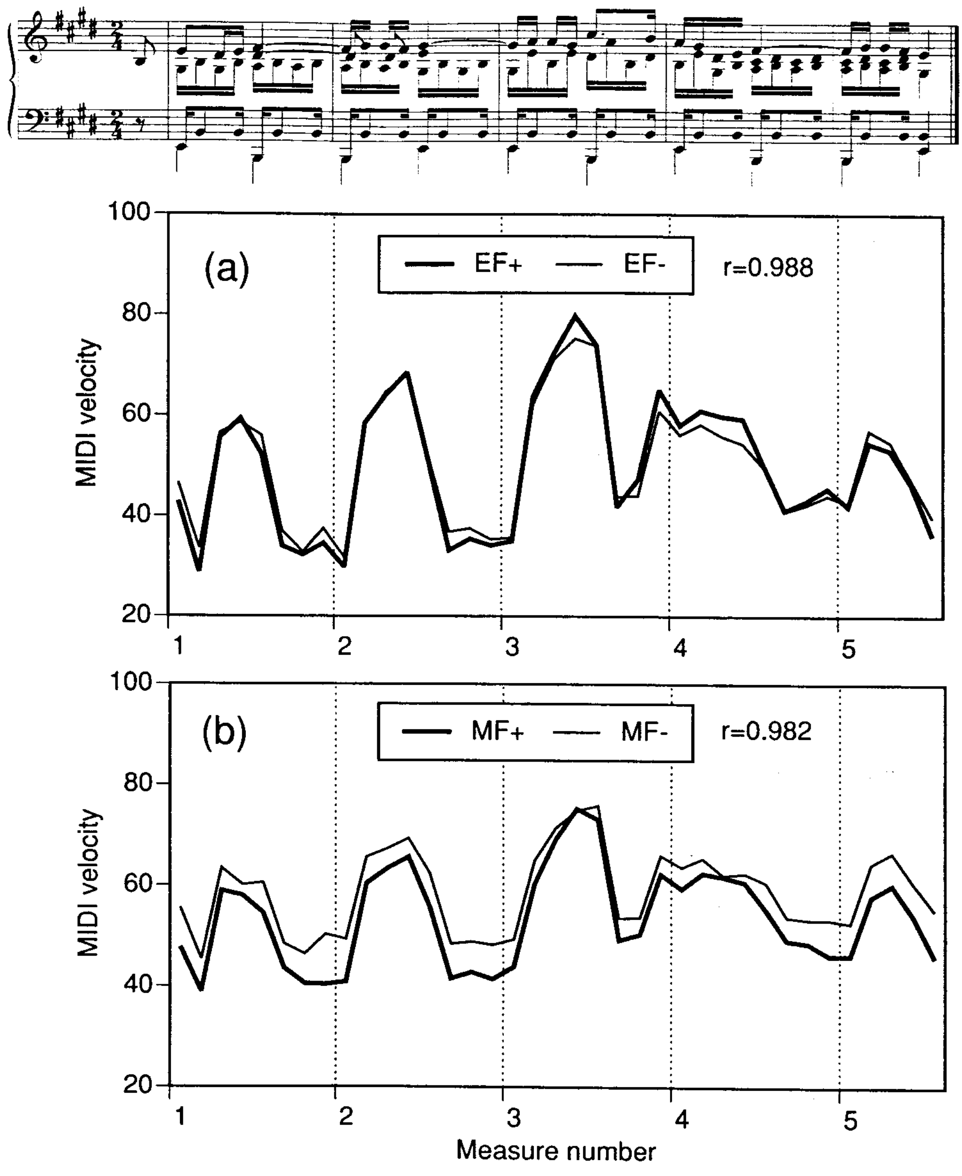

Fig. 4. The average expressive dynamic profiles (primary-note velocities) in the four playing conditions. EF+ = expressive with auditory feedback, EF– = expressive without auditory feedback, MF+ =metronomic with auditory feedback, MF– = metronomic without auditory feedback.

Figure 5 shows the average standard deviations of the MIDI velocities of the primary notes as a function of their average velocities in the four playing conditions. The negative slopes of the regression lines indicate a tendency for dynamic variability to decrease as dynamic level increased; in

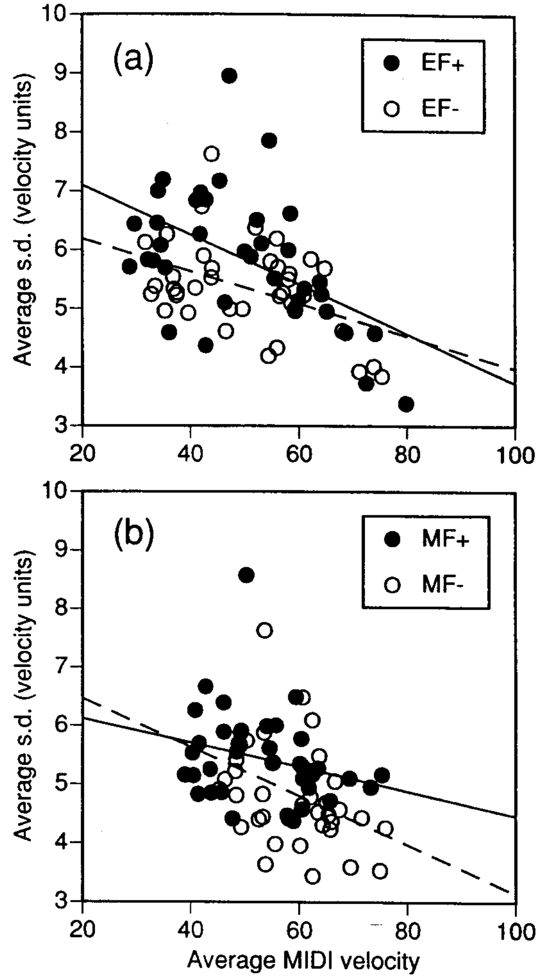

Fig. 5. The relationship between average primary-note velocities and variability in the four playing conditions, with regression lines. EF+ = expressive with auditory feedback, EF− = expressive without auditory feedback, MF+ =metronomic with auditory feedback, MF− = metronomic without auditory feedback, s.d. = standard deviation.

other words, melody notes tended to be less variable than accompaniment notes. This tendency was reflected in a highly significant main effect of position in the three-way ANOVA, $F(36,180) = 3.07, p < .0001$, which did not interact significantly with task or feedback and was also significant for each task separately. No other effects were significant, which means that there was no evidence for any change in dynamic variability in the absence of feedback.

In summary, clear evidence exists for a reduced dynamic range in metronomic performance, and also for a slight reduction when feedback is absent, in both expressive and metronomic performance. Dynamic variability, however, seems unaffected by the absence of feedback. Like expressive timing, dynamic control is not seriously disrupted by the withholding of auditory feedback.

Vertical Timing

Vertical timing refers to the asynchronies among nominally simultaneous note onsets. These values and their standard deviations were computed initially with reference to the primary notes, because this is how the individual data had been coded. For graphic presentation, however, the average asynchronies were recomputed relative to the alto voice because this is the only voice that has a note onset in every sixteenth-note position (see Figure 1). There were 62 asynchronies altogether, due to 22 soprano notes, 11 mezzo notes, 19 tenor notes, and 10 bass notes. It would lead too far to discuss here the detailed asynchrony patterns as a function of position in the music. Instead, the data are presented in the form of scatter plots pitting the F+ and F– conditions against each other.

Figure 6 shows these plots for the expressive and metronomic tasks. Negative asynchronies represent a temporal lead relative to the alto voice; positive asynchronies, a temporal lag. It is clear that the different voices had different temporal relationships with the alto voice. The soprano melody notes preceded the alto notes by up to a few tens of milliseconds (note that both were played by the right hand); such "melody leads" are commonly observed in piano performance (see Palmer, 1996; Repp, 1996b). The mezzo notes, also played by the right hand, tended to lag behind the alto notes, which is consistent with Repp's (1996b) observation that inner notes of chords tend to lag behind outer notes. The tenor notes, played by the left hand, sometimes led and sometimes lagged behind the alto voice, and the bass voice more often lagged than led.[6] Within each voice, there was systematic variation as a function of position, which is reflected in the high positive correlations between the F+ and F– conditions for each voice, listed in Figure 6.

The statistical analysis was performed on the asynchronies computed relative to the primary notes, which were predominantly positive (i.e., lags) because the primary notes tended to lead.[7] The four voices were not distinguished, so that the position variable—more appropriately called "Note" here—had 62 levels. The three-way ANOVA showed a significant main

6. However, individual differences with regard to the timing of the bass voice were substantial. One pianist in particular (M. S.) often led with the bass voice, especially where it coincided with melody notes, and a second pianist (K. S.) also showed a tendency in that direction. This corroborates Repp's (1996b) observation that some young pianists have a tendency to lead with the left hand whereas others do not.

7. The fact that the statistical analyses were done on a data representation different from that in the graphs is awkward, but recoding of all individual data would have been extremely time-consuming.

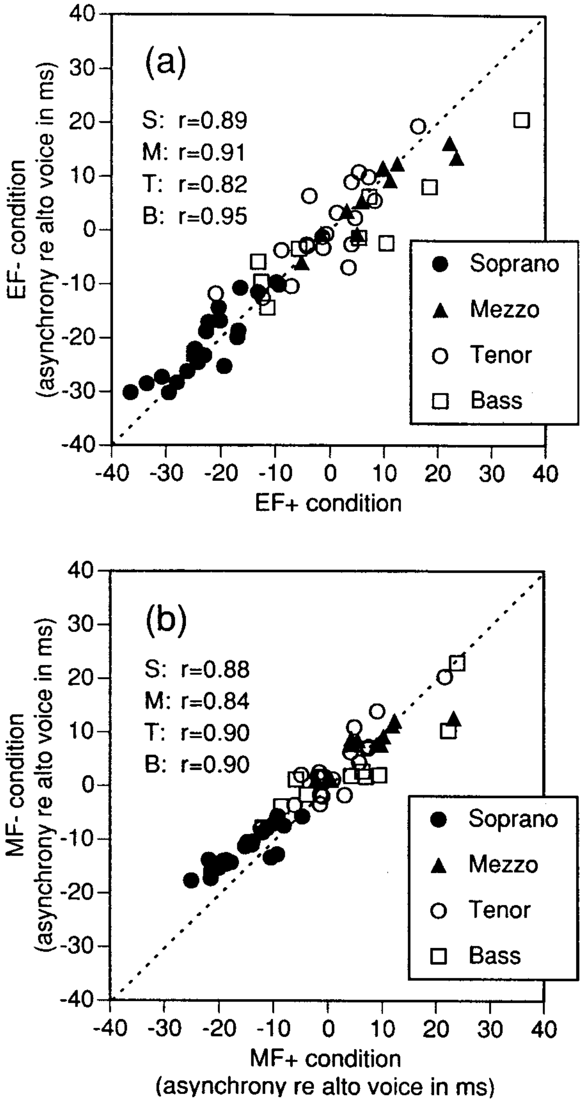

Fig. 6. The relationship between note onset asynchronies (relative to the alto voice) with and without feedback, for (a) expressive and (b) metronomic playing conditions. The dotted line is the major diagonal, not a regression line. EF+ = expressive with auditory feedback, EF– = expressive without auditory feedback, MF+ =metronomic with auditory feedback, MF– = metronomic without auditory feedback.

effect of task, $F(1, 5) = 12.45$, $p < .02$, reflecting somewhat shorter asynchronies (i.e., shorter lag times) overall in the metronomic tasks. This is reflected in Figure 6 by a narrower range of asynchronies in the metronomic than in the expressive tasks. (A main effect in the asynchronies re primary notes becomes an interaction with note in the asynchronies re alto notes, and conversely an interaction may become a main effect.) The main effect of feedback was just significant, $F(1,5) = 6.93$, $p < .05$, owing to slightly longer lag times in the F+ than in the F– tasks. Feedback also interacted significantly with note, $F(61, 305) = 1.59$, $p < .007$, but not with task. These effects are reflected in Figure 6 by the slightly narrower range of asynchronies without than with feedback. In the separate two-way ANOVAs on the expressive and metronomic tasks, the main effect of feedback did not reach significance for either type of task, and the Feedback × Note interaction was significant only in the expressive tasks, $F(61, 305) = 1.48$, $p < .02$.

The average standard deviations of the asynchronies (re primary notes) ranged from 7 to 20 ms, with a few longer values in the expressive conditions. No significant relationship was found between asynchrony magnitude and variability. Nevertheless, systematic differences in variability were apparent among different asynchronies, as shown by a highly significant main effect of note in the three-way ANOVA on the standard deviations, $F(61, 305) = 3.40$, $p < .0001$. This main effect was also highly significant in the separate two-way ANOVAs on the two tasks. The three-way ANOVA also showed a significant main effect of task, $F(1,5) = 26.97$, $p < .004$, owing to larger variability in the expressive than in the metronomic tasks. No significant main effect of feedback was seen, but a significant Feedback × Note interaction was noted, $F(61, 305) = 1.54$, $p < .01$. In the two-way ANOVA on the expressive tasks, the Feedback × Note interaction was also significant, $F(61, 305) = 1.43$, $p < .03$, but not in the two-way ANOVA on the metronomic tasks. Instead, the metronomic tasks showed a significant main effect of feedback, $F(1, 5) = 9.80$, $p < .03$, because of somewhat *smaller* variability in the absence of feedback.

To summarize the results of this section: Not much evidence was found for systematic effects of feedback deprivation on vertical timing. Asynchronies tended to be somewhat restricted in range and, if anything, *less* variable in the absence of feedback. Metronomic playing clearly reduced the range of asynchronies, especially melody leads.

Vertical Dynamics

Vertical dynamics refers to the relative intensities (here, MIDI velocities) of notes with nominally simultaneous onsets. This aspect of expression relates to chord balance and texture. As with vertical timing, differences in MIDI velocities among nominally simultaneous notes were computed relative to the primary notes for statistical analysis, but the averages were recomputed relative to the alto voice for graphical presentation.

Scatter plots of the MIDI velocity differences are shown in Figure 7. Not surprisingly, the soprano melody was consistently more intense than the alto voice. The relative intensity of the mezzo notes varied greatly as a

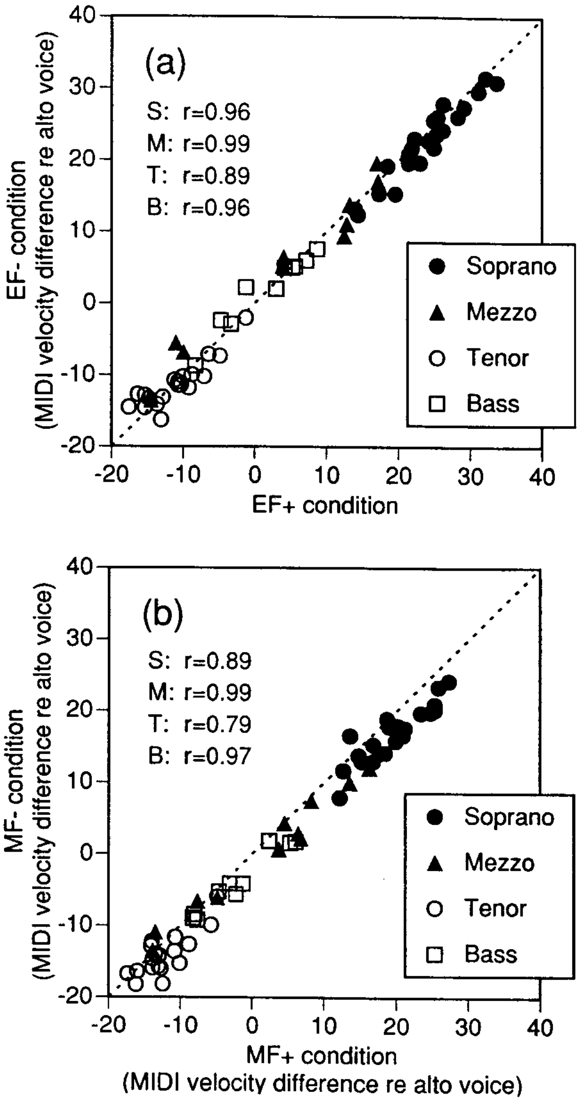

Fig. 7. The relationship between velocity differences (relative to the alto voice) with and without feedback, for the (a) expressive and (b) metronomic playing conditions. The dotted line is the major diagonal, not a regression line. EF+ = expressive with auditory feedback, EF– = expressive without auditory feedback, MF+ =metronomic with auditory feedback, MF– = metronomic without auditory feedback.

function of position in the music, being sometimes above and sometimes below the alto voice. The tenor voice was generally softer than the alto voice, and the bass notes were of approximately the same intensity as the alto notes. The differences within each voice as a function of position in the music were systematic, as is indicated by the very high correlations between the two feedback conditions for each voice, listed in the figure. The correlations were lower for the tenor voice, probably because of the limited dynamic range of that voice (which had a purely rhythmic function).[8]

The three-way ANOVA and the subsequent two-way ANOVAs on all voices combined showed highly significant note main effects. In the three-way ANOVA, a Task × Note interaction was highly significant, $F(61,305) = 3.97, p < .0001$, owing to a compression of the vertical dynamic range in the metronomic tasks (see Figure 7). This compression is consistent with (and partially identical to) the compression of the horizontal dynamic range noted earlier (Figure 4), which involved primary notes only. A main effect of feedback also was found, $F(1, 5) = 11.11, p < .03$; a Feedback × Note interaction, $F(61, 305) = 1.58, p < .007$; and a triple interaction $F(61, 305) = 1.44, p < .03$. The two-way ANOVA on the expressive tasks showed only a main effect of feedback, $F(1, 5) = 9.52, p < .03$, indicating a slight reduction in the velocity differential between primary and secondary notes. The two-way ANOVA on the metronomic tasks showed only a Feedback × Note interaction, $F(61, 305) = 1.85, p < .0005$. The fact that nearly all data points in Figure 7b fall below the main diagonal indicates that this interaction was due to an increase in the intensity of the alto voice relative to all other voices when feedback was absent.

The standard deviations of the MIDI velocity differences (re primary notes) ranged from 4 to 10 velocity units (about 1–3 dB in terms of peak sound level; see Repp, 1997a). Although softer (i.e., accompaniment) primary notes tended to be more variable than louder (i.e., melody) primary notes (Figure 5), no relationship was apparent between velocity difference and variability among the secondary notes. Nevertheless, systematic differences in variability among the notes were present, as evidenced by highly significant main effects of note in the three-way and two-way ANOVAs. No other effects in these analyses were significant, although the main effect of feedback approached significance in the metronomic tasks, where variability tended to be smaller in the absence of feedback.

In summary, absence of feedback led to a small increase in the relative intensity of the alto voice and hence to a reduction of the dynamic range within the right hand. Variability of vertical dynamics was little affected.

8. The relationship between the average asynchronies and the average velocity differences (both computed relative to the alto voice) across notes was also investigated. Overall correlations ($n = 62$) in the four playing conditions ranged from –.64 to –.69 (all $p < .001$): The louder one note was relative to another, nominally simultaneous note, the more its onset tended to precede that of the other note. Correlations within the right hand (soprano and mezzo voices combined) ranged from –.78 to –.83 and thus revealed an even tighter relationship between vertical timing and vertical dynamics. By contrast, correlations between hands (tenor and bass combined, measured relative to the alto voice in the right hand) ranged only from –.17 to +.07 (all n.s.), indicating that the relative timing of left- and right-hand notes was not predictable from their dynamic relationships. These results are in good agreement with those of Repp (1996b), which had been obtained on a computer-controlled acoustic piano (Yamaha Disklavier).

Pedaling

Depression of the sustaining (or damper) pedal prevents the dampers from touching the strings and thus prolongs the durations of tones whose keys have been released, until the pedal itself is released. Pedal actions have two aspects (Repp, 1996a): (a) *Pedal use,* that is, how frequently the pedal is depressed and released, and where in the music these actions occur (with reference to the printed score), and (b) *pedal timing,* the exact times at which the pedal is depressed and released (in relation to preceding and following tone onsets). In the present musical excerpt, the pedal is depressed almost continuously and is punctuated only by *pedal changes* (i.e., the quick succession of a pedal release and a pedal depression). The number and locations of pedal changes therefore provide a sufficient characterization of pedal use in this excerpt. Only number will be discussed here. Pianists must change pedal at least with every harmonic change in the music (i.e., 6 times; see Figure 1) or, perhaps more realistically, with each beat (9 times), but if they wish they can also change pedal with every melody note and even with the accompaniment notes in the second half of bar 4 (i.e., as often as 28 times). Only the accompaniment notes in bars 1–3 would seem unlikely candidates for pedal changes.

Because of considerable individual differences in the pedaling results, these data are shown and discussed at the individual level. Indeed, an overall two-way ANOVA on the pedal change frequencies revealed no significant effects of either task or feedback, even though there were striking effects for individual pianists. Figure 8 shows the pedal change frequencies in the four playing conditions for each of the six pianists. The small standard errors indicate that all pianists were rather consistent in their pedal use across performances within conditions. When auditory feedback was available, B. R., the only real amateur in the group, pedaled much more frequently than the young professionally trained pianists. In the absence of feedback, however, his frequency of pedal use decreased dramatically, $F(1, 36) = 139.54$, $p < .0001$.[9] D. G. showed a similar but much smaller effect of feedback that nevertheless reached significance, $F(1, 36) = 10.92$, $p < .003$. T. C. likewise decreased his pedal use in the absence of feedback, $F(1, 36) = 10.79$, $p < .003$ but also changed pedal less often in the metronomic than in the expressive tasks, $F(1, 36) = 53.84$, $p < .0001$. The same was true for H. S., who showed significant main effects of both task, $F(1, 36) = 15.09$, $p < .0005$, and feedback, $F(1, 36) = 41.19$, $p < .0001$. K. S. differed from the other five pianists in that she showed a significant *increase* in pedal change frequency in the absence of feedback, $F(1, 36) = 45.18$, $p < .0001$, which was more pronounced in the expressive than in the metronomic tasks, $F(1, 36) = 18.51$, $p < .0002$, for the interaction. She also

9. The individual analyses were repeated-measures ANOVAs with performances within playing conditions as the random variable.

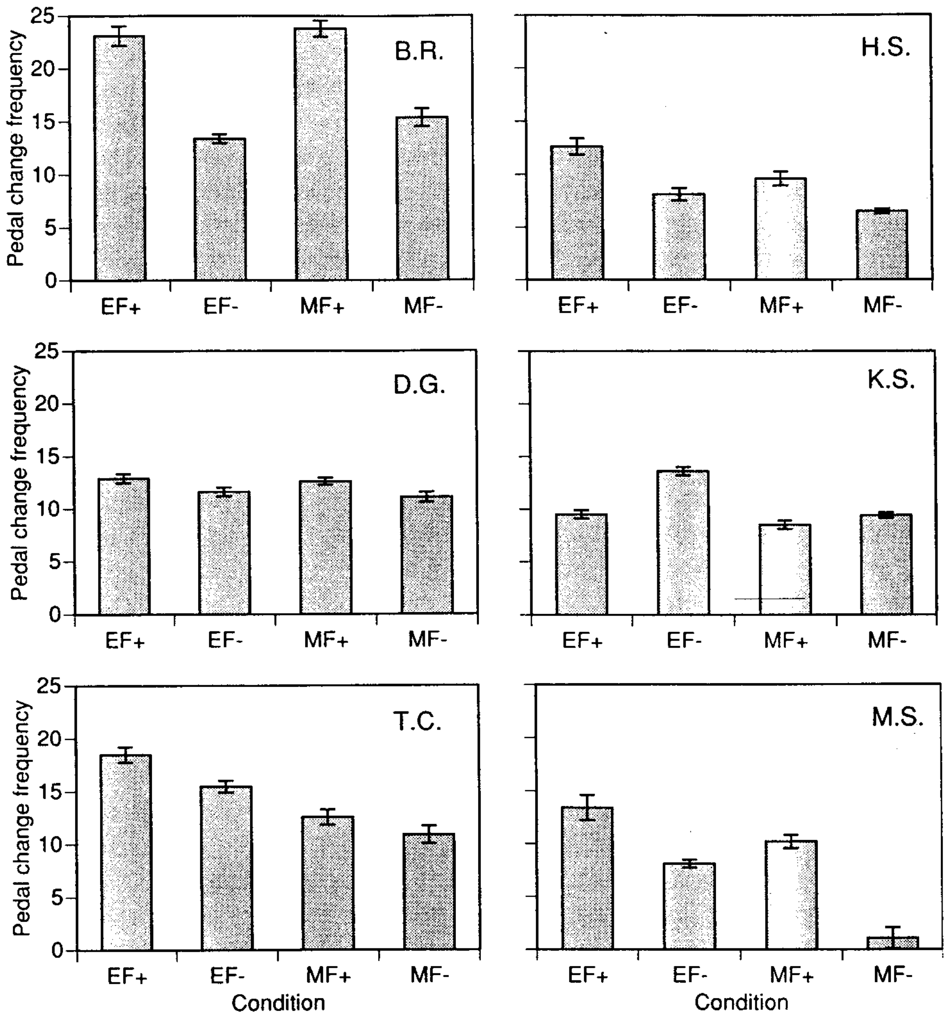

Fig. 8. Average absolute pedal change frequencies in the four playing conditions for each of the six pianists, with ±1 standard error bars. EF+ = expressive with auditory feedback, EF– = expressive without auditory feedback, MF+ =metronomic with auditory feedback, MF– = metronomic without auditory feedback.

pedaled significantly less in the metronomic than in the expressive tasks, $F(1, 36) = 48.87, p < .0001$. Finally, M. S. again showed large effects of both task, $F(1, 36) = 35.23, p < .0001$ and feedback, $F(1, 36) = 70.21, p < .0001$, as well as a weak interaction, $F(1, 36) = 4.89, p < .04$, due to the regrettable fact that she did not pedal at all in the last eight performances of the MF– condition. Even if this condition is disregarded, M. S. nevertheless showed significant effects of task, EF+ vs. MF+: $F(1, 18) = 5.62, p < .03$, and of feedback, EF+ vs. EF–: $F(1, 18) = 17.89, p < .0006$.

The exact time of each pedal release and depression was expressed as a percentage of the IOI in which it occurred (i.e., relative to the onsets of the preceding and following primary notes). A negative percentage (of the following IOI) was computed for a pedal release that immediately preceded a note onset. These percentages were then averaged across the 10 performances in each condition, and the averages were edited to eliminate those based on only a single occurrence or showing abnormally large variability. Figure 9 shows scatter plots of the remaining average pedal times in the two expressive tasks for the six pianists. (Scatter plots for the two metronomic tasks looked quite similar to Figure 9 and therefore are not shown separately.) Pedal releases typically occurred soon after the onset of a primary note, which created the desired legato effect. However, T. C. (and occasionally B. R., D. G., and M. S. as well) had a tendency to release the pedal early, whereas H. S., K. S., and especially M. S. often released the pedal rather late, thereby producing considerable overlap between successive tones. Pedal depressions generally followed pedal releases in the same IOI and therefore occurred later, although their exact time varied greatly with position in the music. This variation was systematic, as is evidenced by the clustering of the data points around the main diagonal. The correlations shown in the figure were computed across pedal releases and depressions combined. Four pianists showed very high correlations between the EF+ and EF– conditions. D. G. and M. S. had lower correlations, in each case due to a single outlier.[10]

Because the locations of pedal changes were not entirely consistent across performances, the matrix of pedal timing data contained many empty cells. Therefore, the data were not subjected to statistical analysis. No systematic effects of either task or feedback on pedal depression times were found. Pedal releases, however, tended to occur a little earlier when feedback was absent (i.e., the data points in Figure 9 fall below the main diagonal), especially for D. G., H. S., and K. S. The same tendency was present for all five pianists in the metronomic tasks. (M. S.'s metronomic data could not be examined because of her neglect of pedaling in the MF– condition.) Thus, deprivation of feedback led to a slight reduction of the legato overlap between successive notes. A similar reduction could be observed in the metronomic relative to the expressive tasks. Judging from the results of earlier analyses, these differences were probably statistically reliable.

In summary, the pedaling data revealed fairly substantial effects of feedback and task on pedal use in some pianists: The pianists changed pedal less frequently when feedback was absent and when they played metronomically rather than expressively. This decrease in frequency of

10. In D. G.'s case, this data point represents the first pedal depression right after the initial upbeat, which he for some reason made much later in the absence of auditory feedback. In M. S.'s case, however, the outlier represents a pedal depression in bar 4.

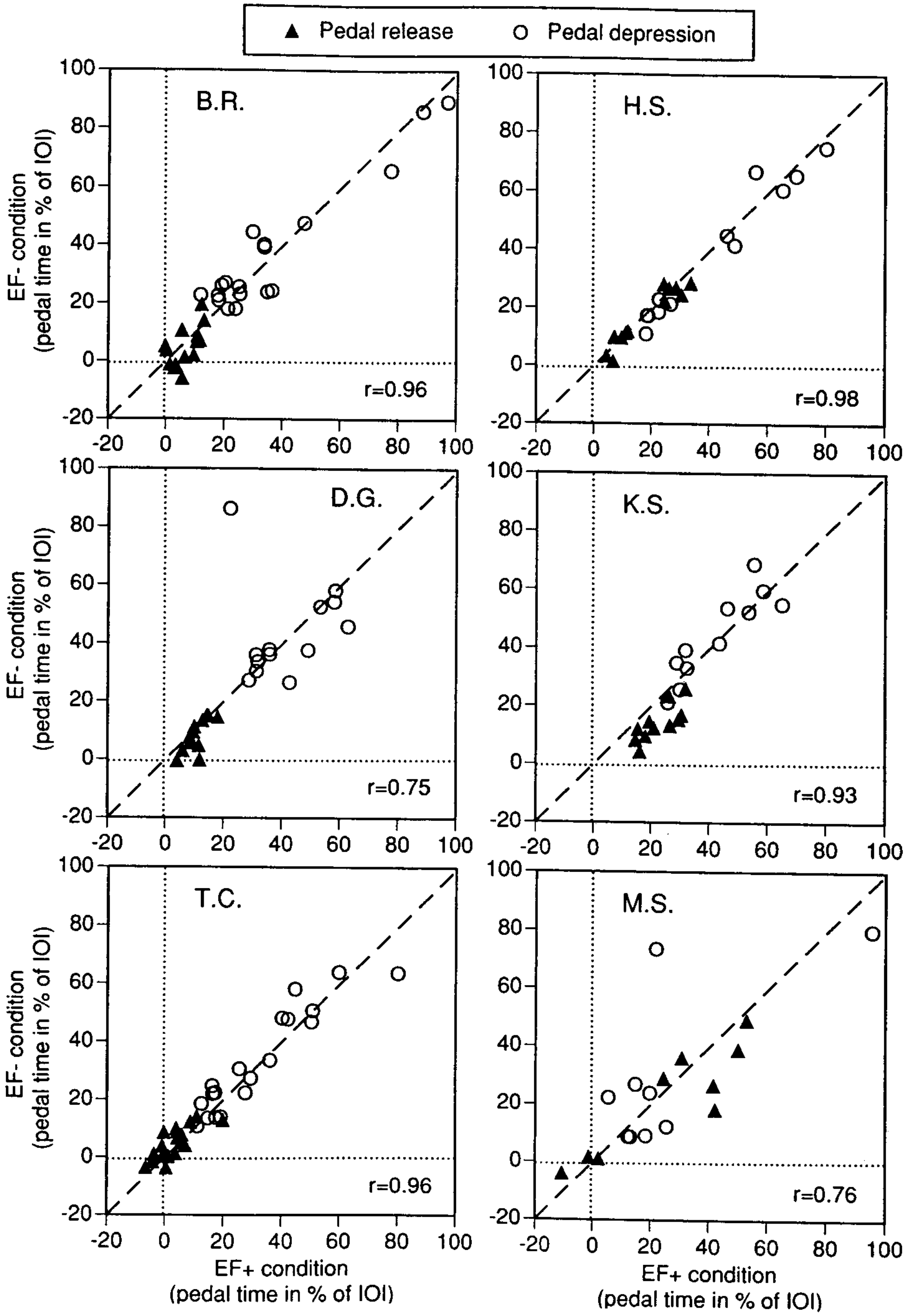

Fig. 9. The relationship between pedal event times (expressed as a percentage of the interonset interval in which they occurred) with and without feedback, for each of the six pianists. The dashed lines are the major diagonals, not regression lines. EF+ = expressive with auditory feedback, EF– = expressive without auditory feedback, MF+ =metronomic with auditory feedback, MF– = metronomic without auditory feedback, IOI = interonset interval.

changing pedal was accompanied by a tendency to reduce the extent of pedal legato.

Perceptual Test

The perceptual test was conducted to determine whether the expressive performances played without auditory feedback were in any way aesthetically inferior to the expressive performances played with normal feedback.

METHOD

Materials

The materials were the 120 performances of the EF+ and EF– conditions (6 pianists, 2 conditions, 10 repetitions). For each pianist, 10 pairs of performances were constructed by pairing the first EF+ performance with the first EF– performance, the second with the second, and so on. In half of these pairs, the EF+ performance preceded the EF– performance, and in the other half the order was reversed. The assignment of these orders to pairs was random and different for each pianist.

Participants and Procedure

Ten Yale undergraduates, all pianists with fairly advanced skills (but not including K. S. and M. S.), were paid for their participation. They sat in front of a computer monitor, listened to the performances over Sennheiser HD 540 II earphones, and responded by clicking with the mouse on a response panel displayed on the monitor. The experiment was controlled by a MAX patcher (i.e., program) constructed for that purpose. The patcher played back the performances (stored as MIDI text files) on the Roland RD-250s digital piano, on which they had been recorded. Performances within a pair were separated by 1 s of silence. Participants played a pair by clicking a button on the response panel, then clicked one of two buttons to enter a decision of "first" or "second" in response to the question "Which performance was played without feedback?", and finally clicked one of three buttons labeled "quite confident," "not so sure," and "just guessing" in response to the question "How confident are you about your decision?" The instructions pointed out that identifying the performance played without feedback was tantamount to identifying the poorer performance in each pair. The performances were presented in 6 blocks of 10 pairs each. Each block represented one pianist, and the order of blocks was different for each participant. Within each block, the order of pairs was the same for all participants. After each block, the MAX patcher displayed the number of correct responses on the bottom of the panel and saved the responses in a file. A brief pause followed during which the participant answered in writing the question "In what way(s) do you believe did this pianist's performances without feedback differ from those with feedback?" while the experimenter loaded the next block of trials. The whole session took about 75 minutes.

RESULTS AND DISCUSSION

As expected, the task was quite difficult. The overall percentage of correct judgments was 63.5, which was significantly better than the chance level of 50%, $t(9) = 4.37$, $p < .003$, across participants; $t(5) = 4.36$, $p < .008$, across pianists. The scores of individual participants ranged from

52% to 77% correct, and those for individual pianists ranged from 52% (M. S.) to 70% (D. G.). Only four of the 60 individual stimulus pairs showed average scores of 30% or lower, which indicates that few clues were consistently misleading. The average confidence rating was 2.2 (where 1 = just guessing, 2 = not so sure, 3 = quite confident). However, the participants' confidence in correct judgments (2.22) was not significantly higher than their confidence in incorrect judgments (2.16).

The participants' written comments referred to all relevant aspects of the performances, although not with equal frequency. References to timing were common for those four pianists whose timing was highly modulated: Their EF– performances were thought to exhibit "rhythmic inconsistency," "tempo instabilities," and "lapses in tempo control." For the two pianists who played with less expressive timing modulation (T. C., M. S.), comments on timing were nearly absent. Only one participant noticed the large difference in final ritards in K. S.'s EF+ and EF– performances, and another participant in T. C.'s performances; their judgments indicated that they correctly interpreted the longer ritard as indicating absence of feedback. Two participants observed that the final chords were released abruptly in H. S.'s EF– performances.[11]

Comments on both horizontal and vertical dynamics were frequent. Performances without feedback were believed to be characterized by such flaws as "undue emphasis on downbeats," "notes that stick out," "large swings in dynamics," "unintentional accents," "less control of volume," and "sudden dynamic change." Participants also noted such things as "left hand comes in heavier," "no contrast in the different voices," "melody was not given sufficient prominence," "balance between the voices was worse," "melody protruding unmusically," "depth of sound differed," and "more bass." These latter comments correspond to the observed reduction in dynamic contrast among the voices (Figure 4).

Comments on pedaling were also frequent, especially on the performances by M. S. ("pedal playing was choppier," "pedal control lacking," "blurry") and also on those by D. G. and H. S. The pedaling of B. R., which exhibited the largest changes as a consequence of feedback deprivation (Figure 8), was commented on by only three participants. T. C. and K. S. received only a few pedaling comments.

Comments on asynchronies were very rare (a total of three, out of 60 opportunities). Some comments were difficult to interpret ("clarity of phrase," "lack of finger control," "roundedness of chords," "articulation overdone," "phony-sounding and contrived"). Although each participant made many pertinent observations on each pianist's performances, in view

11. This rather obvious flaw had not been detected in the performance analyses because articulation was not analyzed. It indicates negligence rather than lack of timing control and evidently was not given much weight by the participants.

of the low discrimination scores, many of these impressions must have referred to flaws that were shared equally by EF+ and EF– performances but differed randomly from pair to pair, thus giving the impression of a valid cue. Some comments may also reflect merely what the participants believed to be possible consequences of feedback deprivation.

General Discussion

The present results basically confirm Finney's (1997) observation that absence of auditory feedback does not seriously disrupt keyboard performance, and they extend this finding specifically to expressive performance. Expressive timing and dynamics in both their horizontal and vertical aspects were highly similar with and without feedback, and performances from the two playing conditions were difficult to discriminate on aesthetic grounds. This indicates that the complex motor activities of performance are guided by a mental representation that includes not only the musical structure but also fine expressive detail. In other words, the expressive features are prespecified and are implemented without extensive reliance on auditory feedback. This is not to deny that normal auditory feedback is vitally important in learning a piece, refining its interpretation, and fine-tuning a performance to an unfamiliar instrument or acoustic environment. Once this has been accomplished, however, expressive performance can proceed largely in a feed-forward manner.

The only performance parameter that was seriously affected by feedback deprivation, and then only in some pianists, was pedal use. This finding is in agreement with Heinlein's (1930) results, mentioned in the Introduction. Most pianists changed pedal less often when they could not hear themselves. In the case of B. R., who showed the largest effect, this may be attributed to his amateur status; he generally pays little conscious attention to pedaling in his informal playing. Pianists who receive professional instruction may have more conscious control over what they are doing with their right foot and therefore may be less affected by feedback deprivation. Nevertheless, four of the five young pianists did reduce their pedaling frequency in the absence of feedback. This suggests an alternative interpretation: Pedaling may indeed depend on auditory feedback to a greater extent than other performance parameters, and B. R. may in fact have paid the greatest attention to the sonic consequences of his pedaling, perhaps because he was more familiar with the (somewhat primitive) instrument. Frequent pedal changes may be necessary on the digital piano to achieve clarity of sound, but in the absence of feedback, pedaling tends to be governed by the musical structure, that is, by harmonic changes or metrical groups. In other words, the detailed sonic consequences of pedaling may not be part of the "audiation" or plan that governs expressive performance, or at least they may not be fully integrated with it. It should be noted, however, that pedal timing was not seriously affected: Whenever a pedal change was carried out, it was generally done at the right time and with the right speed. Thus, hand-foot coordination was not disrupted by the absence of feedback.

Although auditory feedback deprivation had no serious disruptive effects, apart from the reductions in pedal use, it did have subtle effects on nearly every aspect of expressive performance. Contrary to Ebhardt's (1898) old results, there was no consistent tendency to play at a slower tempo in the absence of feedback. The effects that did occur were generally in the direction of making the performance less expressive: The dynamic range, the systematic variation in asynchronies, and the degree of pedal legato all tended to be reduced when feedback was absent. Timing modulation, however, tended to be somewhat greater in expressive performances without feedback, though not in metronomic performances. Evidence was also found for slightly greater between-performance variability of expressive timing in the absence of feedback, whereas the variability of vertical timing and dynamics was unaffected or even slightly reduced in the absence of feedback. These changes in variability may have been contingent upon the changes in the range of variation of these expressive variables and therefore may not reflect impaired motor control.

The experiment was set up so that the performances with feedback preceded those without feedback. It is possible, therefore, that improvements due to practice occurred that counteracted any negative consequences of feedback deprivation. Note, however, that practice would have affected expressive and metronomic performances differently, making the former more expressive but the latter less so. Therefore, the only effects potentially attributable to practice are the increased timing modulation in expressive performance and the decreased timing modulation in metronomic performance, both of which may be considered enhancements of the respective performance styles. Most other effects, however, were shared by expressive and metronomic performance and therefore are most likely consequences of feedback deprivation. These effects represent subtle impairments of expressive features, particularly those relating to differentiation of texture and the singing quality of the melody, both of which are of supreme importance in the Chopin etude.

These effects could be due to marginally reduced motor control in the absence of feedback, and in that case, they provide evidence for a limited role of auditory feedback in achieving optimal expression in performance. However, it is also possible that these effects reflect a reduction in the *motivation* to play expressively, which may inevitably accompany the absence of sound. Music performance is a form of communication, even when the player is the only listener; it is then like a monologue. This communicative aspect is missing when sound is absent, so that the expressive intentions are discharged into a void. The result may be a slight, automatic damping of the expressive intentions. According to this account, performance may be entirely under feed-forward control: The effects of feedback deprivation occur before performance starts. This seems a plausible alternative interpretation of the present findings.

As was pointed out in the Introduction, the present study was concerned with one particular performance situation. One certainly could imagine situations in which larger effects of auditory feedback deprivation might be obtained—for example, if the pianists played the music for the first time, or if they were much less skilled, or if the music posed great technical challenges. It is also possible that experienced concert pianists playing highly rehearsed and memorized repertoire may be able to avoid even the subtle effects demonstrated here. The effects of auditory feedback deprivation are likely to be in inverse proportion to the stability of the performance plan, which in turn depends on performer competence, piece difficulty, and amount of practice.

An issue of secondary interest was the effect of the metronomic playing style on the various expressive parameters. The most obvious effect was a dramatic reduction in timing modulation, but with residual systematic timing variations similar to those in expressive performance (see Penel & Drake, 1998; Repp, in press-a, in press-b). However, the intention to play in strict time also had effects on other performance aspects: The dynamic range was clearly reduced, both horizontally and vertically, as was the range of asynchronies (as shown previously by Palmer, 1989, 1996). These effects are qualitatively similar to those of auditory feedback deprivation, and they can be interpreted in two ways also. They may show that the different performance parameters are not strictly independent of each other, so that a deliberate change in one parameter (timing) results in unintended changes in other parameters. Alternatively, and perhaps more plausibly, these effects may be a consequence of the pianists' explicit intention to play less expressively, which is what metronomic performance requires.[12] The parameter interaction thus may occur before playing starts, in the plan that governs performance. If this is so, then the effects of auditory feedback deprivation may have the same explanation as the side effects of metronomic performance: Both may derive from changed expressive intentions, implicit in one case and partially explicit in the other.[13]

12. One might ask why the other parameters did not *compensate* for the absence of expressive timing. This probably does not happen automatically; it would require explicit instructions to make the performance as expressive without as with expressive timing, and it is unlikely that this could actually be achieved.

13. This research was supported by National Institutes of Health grant MH-51230. I am grateful to Paul Buechler for extensive assistance and to Steve Finney, Henry Shaffer, and two anonymous reviewers for helpful comments.

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