1055

Acoustics, perception, and production of *legato* articulation on a computer-controlled grand piano

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In an attempt to replicate and extend previous results obtained on a digital piano [B. H. Repp, J. Acoust. Soc. Am. 97, 3862–3874 (1995)], the present study analyzed piano tone decay characteristics, musically trained listeners' interactive adjustments of key overlap times (KOTs) in tone sequences, and samples of pianists' *legato* playing in scales and *arpeggi* on a computer-controlled Yamaha Disklavier. On the whole, the results resembled the earlier findings: In both perception and production, KOTs tended to be longer for high rather than for low tones and for relatively consonant rather than for dissonant successive tones. KOTs also increased as tempo decreased in production, but there was no corresponding effect in perception (where a smaller range of tempi was used). Even though the decay times of the natural piano tones were about twice as long as those of the digital piano used earlier, the average KOTs were not shorter; on the contrary, they were longer in the perception task, while there was little difference in production. Perception of optimal *legato* does not seem to rest on an invariant criterion of acoustic tone overlap, and pianists do not seem to adjust their KOTs substantially when playing on different instruments. However, there were large individual differences in KOTs. [S0001-4966(97)00809-6]

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INTRODUCTION

Differences in articulation are an important ingredient of technically competent and expressive performance on many instruments. The term "articulation" refers to the manner in which tones are initiated, terminated, and connected to following tones. Keyboard players, unlike string and wind instrument players, do not have much control over the onset characteristics of tones, so that articulation on the piano is mainly a matter of connecting or separating consecutive tones. Connected tones are produced by releasing a key at or slightly after the moment at which another key is depressed.[1] This articulation is called *legato*, and the amount of overlap of the two successive key depressions will be referred to as *key overlap time* (KOT). A negative KOT indicates that the first key was released before the second key was depressed. If this gap is long enough, it will cause the two tones to be perceived as unconnected or *nonlegato*, and if the first tone is in addition rather short, its articulation is referred to as *staccato*.

The present study complements an earlier study of *legato* articulation on a computer-controlled digital piano (Repp, 1995). That instrument (a Roland RD-250s) produced synthetic piano tones that did not have all the variability of natural piano tones. The keyboard was weighted but did not have the exact feel of a real piano, and the sound output was heard over earphones. For these reasons, the generalizability of the findings to real pianos was not assured. It was the purpose of the present study to repeat the earlier measurements and experiments on a computer-controlled grand piano (Yamaha Disklavier). Relevant earlier literature, including the pioneering study of Kuwano *et al.* (1994), is reviewed in Repp (1995).

Repp's study had three parts. First, an acoustic analysis of the tones produced by the digital piano was conducted, in order to describe the sonic environment within which the following perception and production experiments took place. Of main interest were the decay characteristics of the tones, especially the decay following key release, called the *postrelease decay*. In a real piano, this decay includes not only the decay of the damped string vibrations but also the decay of soundboard vibrations and of acoustic reverberation in the room. There is little information about postrelease decay times in the piano acoustics literature. Repp's measurements indicated that these decay times can be up to several hundreds of milliseconds long and that low tones decay more slowly than high tones (as they do prior to key release). However, it is not clear how representative these decay times are of real piano tones, and since they may be instrument- and room-specific, they had to be measured in the present experimental setting as well.

The second part of Repp's study was a perceptual experiment in which musically trained participants (including pianists) listened to repeatedly ascending and descending sequences of tones played under computer control on the digital piano and adjusted their KOTs interactively until the sequences sounded optimally, minimally, or maximally *legato*. The listeners' adjustments in the three conditions provided information about the range of KOTs acceptable as *legato*. The tone sequences varied in tempo, register (pitch height), and pitch step size. Since short piano tones, because of their greater intensity at the time of key release, have longer postrelease decay times than long tones, and since low tones have longer decay times than high tones, it was predicted

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that adjusted KOTs would be shorter at a faster tempo and in a lower register, to compensate for the greater acoustic overlap due to the longer postrelease decay. It was also predicted that tones separated by 3 semitones (st) would yield longer KOTs than tones separated by 1 st, due to their greater consonance. Support was found for all three predictions, though there were some interactions that will be discussed in greater detail below.

In the third part of the earlier study, pianists were recorded playing on the digital piano, with optimal *legato* articulation, ascending and descending tone sequences similar to the ones used in the perceptual experiment. Their KOTs were determined from the Musical Instrument Digital Interface (MIDI) recordings. KOTs increased in absolute magnitude as tempo decreased, an effect that is consistent with the perceptual results, although it may well have a kinematic rather than perceptual origin. There was no effect of register, however, suggesting that the pianists did not adjust their KOTs to the different postrelease decay times of high and low tones. KOTs did tend to increase with the relative consonance (pitch step size) of the tones. The data also revealed large individual differences in average KOT (a range from 27 to 145 ms), a tendency of some pianists to play more *legato* with the right hand than with the left (in the same register), and, most interestingly, a highly systematic pattern of KOTs as a function of position in the sequence: KOTs were longest at the beginning of a unidirectional sequence and decreased as the sequence progressed, increasing again after a reversal of direction. This suggested that, even within the *legato* range, KOTs vary systematically with the metrical or melodic structure of the sequence.

The present study was divided into three analogous parts. Its design was similar to, but not identical with, that of the earlier study. The goal of the initial acoustic analyses was to determine the pre- and postrelease decay characteristics of the natural piano tones used in the subsequent experiments. In the perceptual part, listeners controlled KOTs interactively on a Yamaha Disklavier in order to find the optimal, minimal, or maximal *legato* for tone sequences varying in tempo, register, and pitch step size. In the production part, pianists played the tone sequences used in the perceptual experiment, and their KOTs were recorded and analyzed to determine whether adjustment to different amounts of acoustic overlap occurred, as well as to observe other systematic patterns and individual differences. Finally, in a task not included in the earlier study, the pianists were asked to perform a short musical composition involving *legato* articulation, in order to check whether some of the findings extended to the playing of real music.

I. ACOUSTIC ANALYSIS

A. Method

The acoustic measurements to be reported were conducted on the tones of a Yamaha Disklavier Mark II grand piano, the instrument used in the production experiment.[2] It was less than 1 year old at the time of recording and stood in the center of a large classroom, with its lid raised to the highest position. The recording microphone (Shure BG 5.0 cardioid) was pointed at the piano from the right side at a height of about 5 ft, about 3 ft from the curved rim of the frame. Some additional recordings were made from a position in front of the piano, approximately where a pianist's head would be. All recordings were made on digital audio tape.

The tones were produced under the control of a simple program written in MAX (a graphic programming language for MIDI applications), running on a Macintosh computer. The solenoid-driven piano keys were played in ascending order, with nominal intertone (key release to key depression) intervals of 1 s. This allowed each damped tone to die away completely before the next tone started. Tones with a nominal (key depression to key release) duration of 250 ms were played at five MIDI velocities (relative intensities): 20, 40, 60, 80, and 100. At the MIDI velocity of 100, they were also played with two longer nominal durations: 500 and 1000 ms.[3] (Nominal duration was meaningless for tones above F6 because of the absence of dampers.) As in Repp (1995), the analysis was restricted to the five octaves between C2 (65 Hz) and C7 (2093 Hz), but whereas only every third tone in the chromatic scale had been analyzed in the previous study, all tones were measured here.

To conduct these measurements, the digital recordings were resampled by a Macintosh Quadra 660 AV computer at 22.055 kHz/s. SIGNALYZE software was used to compute the root-mean-square amplitude envelope of each tone with a running rectangular integration window. The width of the window was set to 40 ms for tones in the lowest two octaves, but from C4 (262 Hz) to C7 (2093 Hz) it was progressively reduced in millisecond steps to encompass approximately ten fundamental periods. The window duration for the highest tone thus was 5 ms. The reason for this procedure was that, as pitch (and with it, sustained decay rates) increased, the energy peak of the tones became narrower, so that a fixed integration window would have led to an artifactual decrease in peak sound level with pitch. (A fixed 30-ms window had been used by Repp, 1995.)

The amplitude at the envelope peak was determined and recorded. Decay during the sustained portion (prerelease decay) was measured in the 1000-ms tones by determining the envelope amplitude every 100 ms from the peak. Postrelease decay was measured by determining the amplitude at the time of key release (i.e., with the integration window centered on that point in time) and every 50 ms from then on, until the amplitude was near the noise floor.[4] All amplitude values were subsequently converted to sound levels in dB, with an arbitrary reference.

B. Results and discussion

Figure 1 shows the basic relation between MIDI velocity and peak sound level, averaged across all pitches. This relationship was virtually constant across the whole pitch range and was best approximated by a quadratic (not a logarithmic) function. For comparison, the very similar function obtained for the Roland RD-250s digital piano used in Repp (1995) is shown.[5] At low MIDI velocities, a 1-dB change equalled about 2.5 velocity units; at high MIDI velocities, about 5 velocity units. The dynamic range represented is about 23 dB. The full range is likely to be a bit wider, but not by much

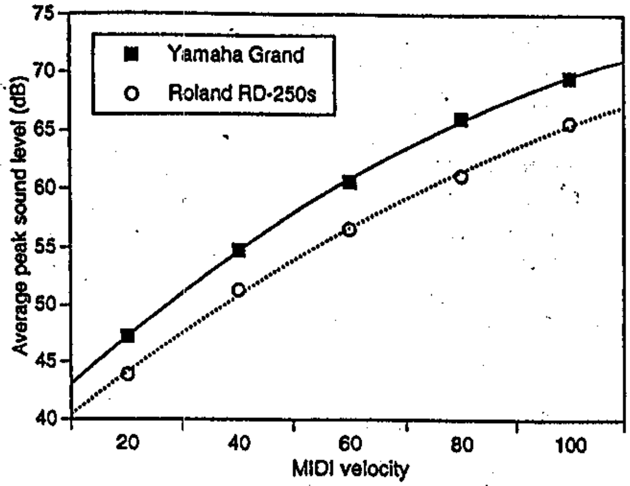

FIG. 1. The increase in average peak sound level with MIDI velocity on the Yamaha Disklavier grand piano and on the Roland RD-250s digital piano ("Piano 1" sound). The curves are quadratic functions fitted to the data points.

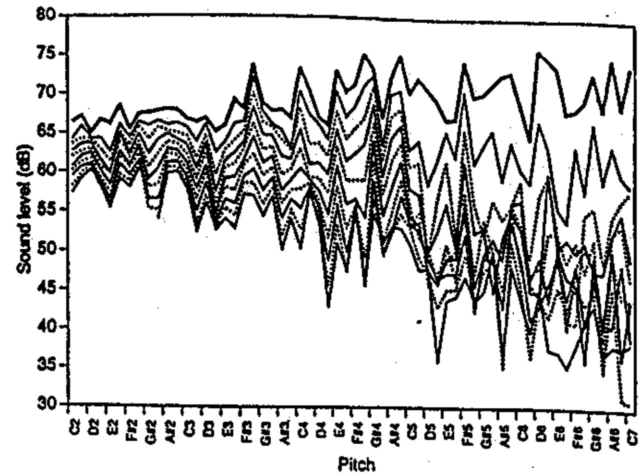

FIG. 3. Prerelease decay contours of tones with a MIDI velocity of 100 and a nominal duration of 1000 ms: Sound levels at the peak (heavy line) and every 100 ms after the peak (solid and dotted lines alternating), until the nominal offset.

because the Yamaha Disklavier does not respond monotonically towards the extremes of the MIDI velocity range (0–127).

Figure 2 shows peak sound levels for all tones as a function of pitch and MIDI velocity. (Two keys in the highest octave failed to produce a sound at the lowest MIDI velocity.) These data suggest that peak intensity was slightly higher in the middle register but did not change very systematically across the pitch range.[6] However, there was large unsystematic variation in peak sound level from one tone to the next, as was observed in earlier measurements on two acoustic instruments (Repp, 1993). The origin of this variation had remained unclear in the earlier study, where only a single microphone position had been used. In the present study, an additional set of tones with a MIDI velocity of 60 was recorded from a position in front of the piano. The dotted line in Fig. 2 represents the peak sound levels of these tones. Clearly, the pattern of the unsystematic variation was

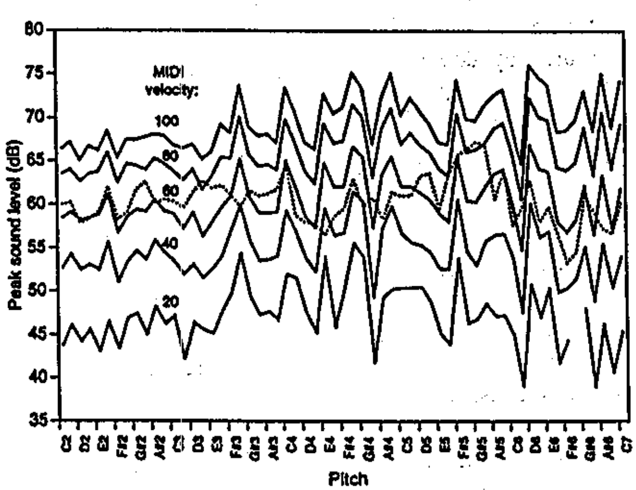

FIG. 2. Peak sound level as a function of pitch and MIDI velocity. The dotted line represents tones with a MIDI velocity of 60, recorded with the microphone in a different position. Only every other pitch label is shown on the abscissa.

largely specific to the location of the microphone. The correlation between the two functions for a MIDI velocity of 60 is only 0.28 ($p<0.05$), whereas that between two functions for the same microphone location (MIDI velocities of 60 and 80) is 0.97. Evidently, then, the irregularities do not originate in the piano mechanism but rather are due to sound radiation in the room (see Benade, 1976).

Next we consider the sustained (or prerelease) decay of the piano tones. Figure 3 shows the peak sound levels at a MIDI velocity of 100 (heavy line), as well as the sound levels of 1000-ms tones measured every 100 ms after the peak, up to the nominal offset (key release). The figure confirms the well-known fact (Martin, 1947) that higher piano tones decay much faster than lower tones. It also shows that the decay pattern of tones above C5 is very different from that of tones below C5: While lower tones seem to decay at a fairly steady rate (over the first second, at least), higher tones rapidly lose energy (about 15 dB) over the first 200 ms and then decay in a highly irregular and nonmonotonic manner.

Figure 4 portrays the postrelease (damped) decay characteristics for tones with a nominal duration of 250 ms and a MIDI velocity of 100. The heavy line on top shows again the peak levels, and the heavy line immediately below it shows the sound levels at the nominal offset (key release). The remaining functions represent the sound levels every 50 ms after the offset, down to the ambient noise floor. It is evident that the postrelease decay rates do not vary as much with pitch as do the prerelease decay rates, but there are again irregularities at the higher pitches. Tones above F6, which have no dampers, decay very little and very irregularly (cf. also Fig. 3). Similar graphs were obtained for 500- and 1000-ms tones but are not shown here to conserve space.

Estimates of pre- and postrelease decay rates were obtained by fitting linear functions to the decay measurements of each tone, even if the decay was very irregular. The absolute values of the slopes of the linear functions thus provide estimates of average decay rates, over about 900 ms

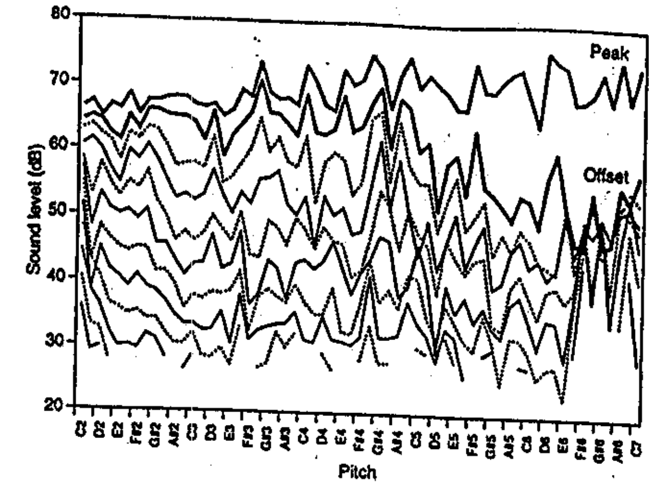

FIG. 4. Postrelease decay contours of tones with a MIDI velocity of 100 and a nominal duration of 250 ms: Sound levels at the peak and at the nominal offset (heavy lines), and every 50 ms from the offset (dotted and solid lines alternating), down to the ambient noise floor.

(sampled every 100 ms) in the case of sustained tones, and over about 500 ms (sampled every 50 ms) in the case of damped tones. Figure 5 summarizes these decay rates, which are expressed in dB per centisecond (cs).

The prerelease decay rates (for 1000-ms tones) increased roughly as a linear function of pitch, from about 1 dB/cs to nearly 3 dB/cs, though there was considerable variability from tone to tone, as already observed in earlier studies (Martin, 1947; Hundley *et al.*, 1978). Similar data for a Baldwin grand piano reported by Hundley *et al.* (1978) showed an increase in decay rates from about 1 dB/cs (C2) to about 10 dB/cs (C7). These authors may have been measuring initial decay rates only or used a piano that was tuned with exceptional accuracy. As Fig. 3 indicates, the decay functions of the present tones were quite linear up to C5, but tones higher than C5 showed a much faster (also apparently linear) decay over the first few hundreds of milliseconds, followed by a slower and usually highly irregular decay afterwards. Hundley *et al.* (1978) have shown that the two decay rates result from interference among the multiple strings, due to slight differences in tuning that cause a loss of phase synchrony over time, which results in reduced energy transmission to the soundboard and in beats that modulate the decay (cf. Fig. 3). The lower tones showed a single decay rate here because it usually takes more than one second for their strings to get out of phase.[7] If measured over a longer time, they typically show two decay rates also (Martin, 1947).

Naturally, the postrelease (damped) decay rates were much faster than the prerelease (sustained) decay rates, but there was again remarkable variability from tone to tone. Moreover, while 500- and 1000-ms tones seemed to decay at about the same rates, 250-ms tones decayed at a faster rate, for reasons that are not immediately clear. For the longer tones, there was a tendency for postrelease decay rates to decrease as pitch increased, although the lowest tones in the range also exhibited slower decay rates. Presumably, the postrelease decay rates reflect sound reverberation in the acoustic space; the decay of the string and sound board vibrations giving rise to the sound is probably a good deal faster.

The prerelease decay rates of the digital piano tones measured by Repp (1995: Fig. 1) were similar to those of the present Yamaha Disklavier tones, although there was evidence of two decay rates only from C6 on (as compared to C5 in the present data). However, the postrelease decay rates of the digital piano tones (Repp, 1995: Fig. 3) were more than twice as fast as those of the Yamaha tones: They increased from about 11 to 18 dB/cs during the lowest (second) octave, and then increased more slowly to about 22 dB/cs in the sixth octave. Evidently, the digital piano tones simulated a less reverberant environment. This is relevant to a comparison of the earlier results with the results of the following experiments.

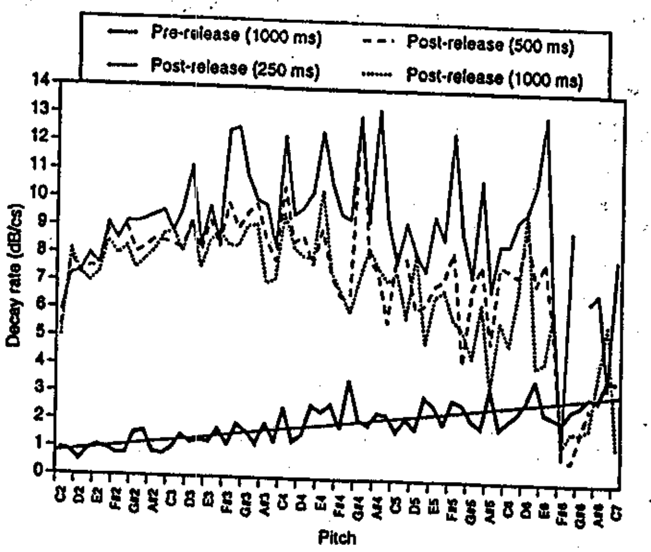

FIG. 5. Average prerelease decay rates for 1000-ms tones and postrelease decay rates for tones of 250-, 500-, and 1000-ms duration. A linear function has been fitted to the prerelease decay rates.

II. PERCEPTION EXPERIMENT

The purpose of this experiment was to determine whether the earlier perceptual results obtained on a digital piano can be generalized to a real acoustic instrument. As in Repp (1995), the task required listeners to adjust key overlap times (KOTs) interactively, so as to achieve a specified degree of *legato* in repeatedly ascending and descending tone sequences. However, the design differed from that of the earlier study in three ways: (1) To vary tempo, the earlier experiment had used tone interonset intervals (IOIs) of 260, 520, 779, and 1039 ms.[8] On the Yamaha Disklavier, the shortest IOIs presented a problem because at the melodic turning points of sequences, where the same tone occurred twice with only one other tone intervening, there was not enough time for the key to be released and depressed again when a long KOT was selected. To avoid missing tones in the sequences, the fastest tempo was omitted and only the three longer IOIs were used. (2) To make up for this reduction in the number of conditions, three rather than two different pitch step sizes were used. (3) Finally, in order to eliminate an earlier confounding of step size with the average pitch of the tones in a sequence, sequences differing in step size were centered on the same pitch. Three registers (octaves) were used, as in the earlier study.

The predictions were the following: (1) The KOT chosen to represent the optimal *legato* should increase with register because damped high tones decay faster and hence show less acoustic overlap than damped low tones. (2) The KOT should increase with IOI because long tones are softer than short tones at the time of key release and therefore decay sooner and overlap less. However, this prediction was confirmed only at the short IOIs (260 versus 520 ms) in the earlier study, and since the shortest IOI was omitted here it was not clear whether an effect of IOI should be expected. (3) The KOT should increase with step size because the successive tones become increasingly consonant at the pitch steps chosen (1, 2, and 3 st, corresponding to intervals of a minor second, major second, and minor third). (4) All these effects should be enhanced when KOTs are chosen to represent maximal *legato*. (5) According to the earlier results, the (generally negative) KOTs chosen to represent minimal *legato* should primarily show an effect of IOI: The longer the IOI, the longer the nominal gap that can be tolerated between successive tones. (6) All these effects will have to be fairly robust to emerge from the considerable variability seen previously in listeners' perceptual judgments. This variability was expected to be increased further by the unsystematic acoustic variation inherent in natural piano tones and the unpredictable effects of room acoustics.

A. Method

1. Listeners

Repp (1995) compared pianists with nonpianists and did not find any systematic differences in their judgments. Therefore the present listeners were only required to have some musical training and thus presumably a concept of *legato*. Fifteen individuals participated, 13 of whom were of college age, recruited by advertisement, and paid for their services; the other two were the author and his research assistant. A wide range of musical experience was represented, ranging from informal music making to more than 10 yr of training on an instrument. Five listeners were pianists. The data of four of the less experienced listeners were excluded because of extreme variability or anomalous responses (large negative KOTs for optimal *legato* in one case, large positive KOTs for minimal *legato* in another). This left data from 11 listeners to be analyzed.

2. Design

The stimuli were continuously ascending and descending 5-tone sequences. There were 27 conditions resulting from the combination of three IOIs, three registers, and three step sizes. The IOIs were 520, 779, and 1039 ms. The registers were the second, fourth, and sixth octave. The step sizes were 1, 2, and 3 st. To keep the average pitch constant within each register, all sequences were centered on G. The 1-st sequence thus consisted of the pitch classes F-F#-G-G#-A, the 2-st sequence of D#-F-G-A-B, and the 3-st sequence of C#-E-G-A#-C#.

3. Procedure

A Yamaha Disklavier Mark II baby grand piano, standing in the same place as the grand piano that eventually replaced it, was controlled by a MAX program running on a Macintosh computer.[9] The listener sat in front of the computer, which stood on a table about 6 feet to the right of the piano, and started and stopped sequences by clicking on "buttons" displayed on the monitor. Also displayed was a "slider" with a "handle" that could be dragged or clicked with the mouse to vary KOT. The slider actually controlled the duration of the tones within a fixed nominal range (250 to 1500 ms). The point of zero KOT on the slider thus varied with the IOI. The slider was unlabeled and was automatically reset to the left-most position (250 ms) at the beginning of each trial, so that the tones in each sequence initially sounded short and unconnected. The listener's task was to start a trial, move the slider first to the right and then back and forth until the tone sequence satisfied the specified perceptual criterion, then to stop the sequence and start the next trial. Each sequence started on its lowest pitch and continued ascending and descending until it was stopped. The MAX program presented the 27 sequences in random order and saved the listener's final slider settings.

After some initial practice, each listener completed four blocks of 27 trials each. In block 1 the task was to find the best *legato* in which the tones seemed "optimally connected." In block 2 it was to find the minimal *legato* in which the tones were "barely connected" but not separated by audible gaps. In block 3 it was to find the maximal *legato* that was still acceptable, without annoying overlap of tones being heard. In block 4 the listeners once again tried to determine the optimal *legato*. Blocks were separated by short breaks. Listeners typically took about 30 s for an adjustment, but there were considerable individual differences in pace. Head movements were not constrained, and listeners were encouraged to turn their head towards the piano while making their KOT adjustments.

B. Results and discussion

The average KOTs chosen by the 11 listeners are shown in Fig. 6, which may be compared to the results on the digital piano shown in Fig. 4 of Repp (1995). The error bars represent ±1 standard error. The results of blocks 1 and 4, which had been averaged in the earlier study, are displayed separately here (as "best 1" and "best 2," respectively) because a change in criterion was evident: Listeners chose longer optimal KOTs (by 54 ms, on the average) at the end of the experiment than at the beginning. The difference was significant in a four-way (block, register, step size, IOI) repeated-measures analysis of variance (ANOVA) on the best *legato* data [$F(1,10)=10.67$, $p<0.009$]. (A trend in the opposite direction had been found in the earlier experiment.) There was large between-listener variability, comparable to that observed in the earlier study. Also in agreement with the earlier findings is even larger variability of maximal *legato* judgments and the small variability of minimal *legato* judgments.

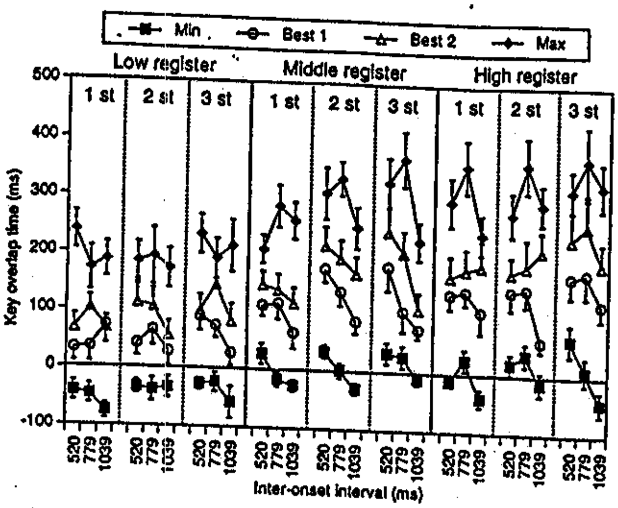

FIG. 6. Perception experiment: Average KOTs and standard error bars for the 27 conditions (3 registers, 3 pitch step sizes, 3 IOIs) in each of four blocks of trials (best 1, min, max, best 2).

Previously, there had also been a clear increase in variability with register, but here there was only a weak tendency in this direction.

There was a pronounced main effect of register in each of the three adjustment conditions, which were subjected to separate ANOVAs. The average KOT for optimal (best) *legato* increased from 73 ms in the second octave to 145 ms in the fourth octave to 169 ms in the sixth octave [$F(2,20)=17.74$, $p<0.0001$], and the average KOT for maximal *legato* increased from 199 to 286 to 320 ms [$F(2,20)=15.48$, $p<0.0001$]. These increases are in agreement with those found on the digital piano, but the KOTs chosen were a good deal longer here, especially in the low register. Evidently, listeners can tolerate more overlap when they listen to a real piano in a room than when they listen to synthetic piano tones over earphones, despite the much longer postrelease decay times of the realistic piano tones. There was also an effect of register on the KOTs for minimal *legato*, though it only contrasted the second with the fourth and sixth octaves: The average KOT increased from -41 to 5 to 6 ms [$F(2,20)=17.75$, $p<0.0001$]. This is also in agreement with the earlier findings, though again the KOTs were longer (i.e., less negative) than before. This is again surprising in view of the slower postrelease decay of the Yamaha tones, which was expected to permit longer nominal gaps in minimal *legato*. On the digital piano, the total range of KOTs that was acceptable as *legato* (max–min) had increased strongly with register; this increase can be seen here, too, but it is less pronounced.

Since the keys above F6 had no dampers, their KOT was not under the listeners' control. Adjustments in the high register (sixth octave) thus derived solely from the two lowest tones in each five-tone sequence. This may account for the relatively small increase in KOTs between the middle and high registers, but it is remarkable that the variability of judgments did not increase substantially in the high register.

The main effect of step size was less pronounced than that of register but nevertheless statistically reliable in each of the three judgment conditions: Average optimal KOTs increased from 111 ms for chromatic scales to 130 ms for whole-tone scales to 146 ms for diminished-seventh *arpeggi* [$F(2,20)=5.49$, $p<0.02$], average maximal KOTs increased from 250 to 266 to 288 ms [$F(2,20)=4.17$, $p<0.04$], and average minimal KOTs increased from -22 to -5 and -2 ms [$F(2,20)=3.85$, $p<0.04$]. This replicates earlier findings on the digital piano. However, there the effect of step size had decreased in the higher registers. Here this was not apparent. The two-way interaction reached significance only for optimal KOTs [$F(4,40)=3.05$, $p<0.03$] but reflected different patterns of the step size effect in different registers, not a decrease in its average size. It is not clear what may have caused those different patterns.

While the preceding effects were fairly straightforward, the effects of IOI (or tempo) were more complex. Average optimal KOTs were 143 ms at the short IOI (fast tempo), 141 ms at the medium IOI or tempo, and 103 ms at the long IOI (slow tempo) [$F(2,20)=6.84$, $p<0.006$]. Thus, rather than increasing monotonically, KOT first remained stable and then decreased with tempo. This trend is actually in agreement with the earlier study, where a decrease at the longest IOI was also observed. The present experiment did not include the shortest IOI of the earlier design (260 ms) which had yielded the shortest optimal KOTs. Thus it seems that the relationship between IOI and optimal KOT is nonmonotonic, with a maximum somewhere between 500 and 800 ms of IOI. The results for maximal *legato* suggest that the maximum may be closer to 800 ms. The average maximal KOTs at the three IOIs were 267, 294, and 242 ms, respectively [$F(2,20)=7.75$, $p<0.004$]. (The earlier data had not shown a decrease at the longest IOI for maximal *legato*.) The results for minimal *legato* showed a monotonic decrease of the average KOT with increasing IOI, from 8 to -2 to -36 ms [$F(2,20)=9.47$, $p<0.002$]. This main effect is in agreement with the earlier findings.

The effect of IOI furthermore interacted with other factors, as had been the case on the digital piano. For optimal *legato*, there were significant interactions of IOI with register [$F(4,40)=2.93$, $p<0.04$] and with step size [$F(4,40)=4.25$, $p<0.006$]. The first interaction is best characterized as an emergence of a difference between middle and high register as IOI increased. The second interaction can be described either as an increase in the effect of IOI (i.e., in the relative decrease in KOT at the longest IOI) with step size or as a disappearance of the step size effect at the longest IOI. These interactions do not correspond to earlier findings. For maximal *legato*, only the interaction of IOI with register was significant [$F(4,40)=3.83$, $p<0.01$]. It, too, suggests an increase in the difference between middle and high registers as IOI increased. For minimal *legato*, the triple interaction between register, step size, and IOI reached significance [$F(8.80)=2.47$, $p<0.02$]. However, it does not reflect an orderly pattern.

Finally, it must be mentioned that there were enormous individual differences. Average optimal KOTs for individual listeners ranged from 18 to 189 ms, maximal KOTs from 86 to 378 ms, and minimal KOTs from -78 to 39 ms. The correlation between listeners' average optimal and maximal

KOTs was 0.62 ($p<0.05$), that between their optimal and minimal KOTs was 0.70, and that between their maximal and minimal KOTs was 0.66. Clearly, the listeners differed greatly in "overlap tolerance," and those with high overlap tolerance also had a low "gap tolerance." These subjective criteria seemed to be unrelated to the instruments the participants had learned to play.

On the whole, these results replicate the findings of Repp (1995). The KOT for optimal legato increases with the average pitch (register) of the tones, evidently because the faster decay of high tones reduces acoustic overlap. It increases with step size, presumably due to the increasing consonance of the tones. It increases with IOI initially (Repp, 1995) but then decreases as the IOI approaches 1 s. The initial increase can be understood in terms of decreasing acoustic overlap, but the decrease at longer IOIs must reflect a different factor coming into play. It is not clear at present what that factor might be.

The present data differ from those for the digital piano in that they show greater tolerance for overlap and less tolerance for gaps, a less pronounced widening of the KOT acceptability range as a function of register, and an increase in the preferred KOT in the course of the experiment, as well as some additional differences in detail.

III. PRODUCTION EXPERIMENT

The purpose of the production task was to replicate Repp's (1995) analogous experiment on a different instrument and to re-examine the relationship between perception and production of *legato*. The earlier study had shown that the KOTs do not pattern in exactly the same way in production and in perception. In particular, pianists did not seem to compensate for the effect of register on tone decay, whereas their KOTs were very strongly and monotonically affected by tempo. Only the effect of pitch step size seemed to be comparable in perception and production. Of additional interest were differences between the two hands and patterns of KOTs as a function of position in the tone sequence.

A. Method

1. Pianists

Nine pianists participated whose level of technical skill ranged from advanced amateur to professional. They included two third-year graduate students (artist's diploma candidates), one first-year graduate student, and one second-year undergraduate (performance certificate) student at the Yale School of Music, four Yale University undergraduates who were skilled pianists, and the author, an amateur. Six of the participants were female. The students were paid for their services.

2. Materials and procedure

Thirty-six music sheets were prepared, each showing a sequence of notes in common (4/4) meter. The sequences matched the ones used in the perception study, except that each consisted of exactly three ascending–descending cycles terminated by a longer final note. The nine sequences in the middle register (fourth octave) were represented twice, with printed instructions to play with either the right or the left hand. The sequences in the low register (second octave) naturally were to be played with the left hand, and those in the high register (sixth octave) with the right hand. Different IOIs were represented by different note values: sixteenth notes, eighth notes, or quarter notes. All sequences were to be played with the fingering 1-2-3-4-5-4-3-2-1 (right hand) or 5-4-3-2-1-2-3-4-5 (left hand). Although this was not necessarily the most preferred fingering for these particular sequences, it was reasonably comfortable at all three pitch step sizes. (This was the reason for centering all sequences on G rather than on some other pitch.)

The pianists were recorded on the Yamaha Disklavier Mark II grand piano from which the acoustic recordings had been made. The piano was connected to a Macintosh computer that recorded the performance in MIDI format. A metronome flashing silently at 60 beats per minute was in view. The pianists were instructed to play at that tempo but in a natural way, not necessarily with mechanical precision. The intended IOIs thus were approximately 250, 500, and 1000 ms, as in Repp's (1995) study. The music pages were shuffled into a different random order for each pianist. Each pianist played the 36 sequences (each of which included three up–down cycles) once.

3. Analysis

Each pianist's MIDI data were imported as text into a spreadsheet program. The different sequences were identified, and their KOTs were calculated by subtracting the onset time of each note from the offset time of the preceding note. Unexpectedly, two of the pianists occasionally held a key down for a very long time (a technique called "finger pedaling"). To avoid distortion of the data by these exceptionally long KOTs, they were replaced by the average of the preceding and following KOTs. Such replacements amounted to about 1% of the data for each of these two pianists.

For the main statistical analysis, the left- and right-hand data for the middle register were averaged. The KOTs were then entered into a five-way repeated-measures ANOVA with the fixed factors register (3 levels), step size (3 levels), IOI (3 levels), position in the sequence (8 levels), and cycles (3 levels).[10] A four-way ANOVA was conducted on each pianist's individual data, with cycles serving as the random factor. Another ANOVA was conducted on the four pianists for whom hand information was available.[11] In this analysis, the two sets of middle-register data were not averaged, and instead of a single factor of register, two crossed but non-independent factors were defined: hand/register (2 levels: left-low and left-middle versus right-middle and right-high) and register within hands (2 levels: left-low and right-middle versus left-middle and right-high). Similar analyses were conducted on the four individual pianists, with cycles as the random factor. Their middle-register KOTs were also analyzed separately, contrasting left and right hands with register held constant.

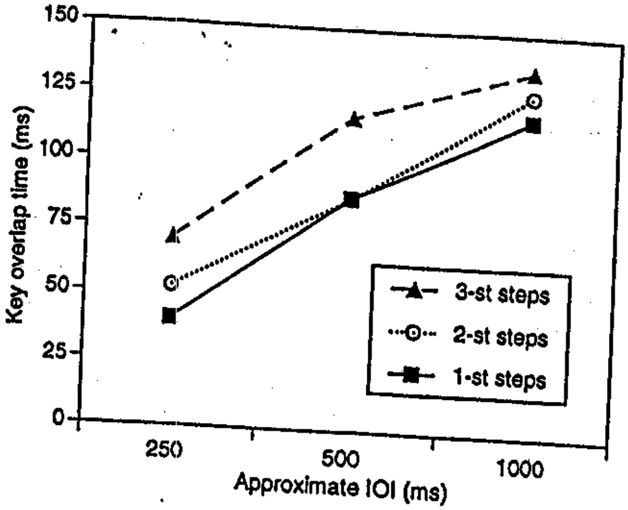

FIG. 7. Production experiment: Average KOTs as a function of (approximate) IOI and step size.

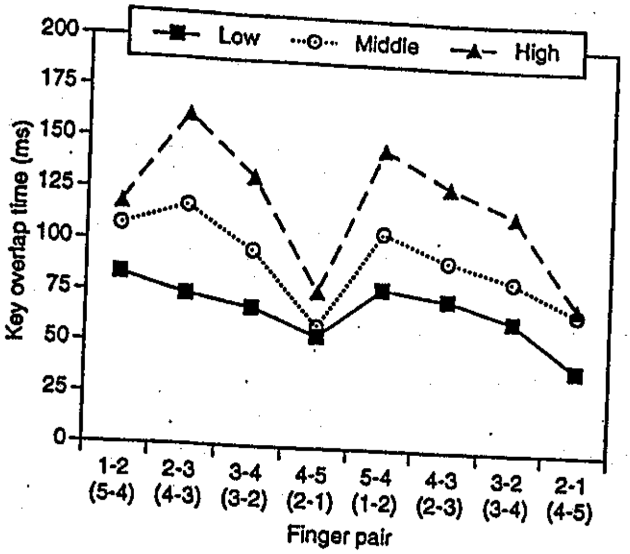

FIG. 8. Production experiment: Average KOTs as a function of position in the sequence (finger pair) and register. Finger pairs in parentheses are for the left hand.

B. Results and discussion

The general range of the average KOTs obtained in the various conditions (about 40 to 140 ms) was similar to that found previously on the digital piano. Despite considerable variability in the raw data, the ANOVAs revealed a relatively simple and highly reliable pattern of results. Figure 7 shows the effects of IOI and step size. The KOTs increased significantly with IOI [$F(2,16)=12.01$, $p<0.001$]. This effect was significant for all nine pianists individually, and it replicates the digital piano data. The KOTs also increased with step size [$F(2,16)=6.93$, $p<0.007$]. This effect was obviously due to the 3-st sequences compared to the other two. All but two individual pianists showed significant step size effects. A similar effect (with 1- and 3-st sequences only) had been found by Repp (1995). The interaction between step size and IOI was not significant.

Two other main effects and an interaction are shown in Fig. 8. KOTs clearly increased with register [$F(2,16)=11.92$, $p<0.001$]. This effect was shown by all pianists but one (the author). Evidently it was not just due to the high register, where the absence of dampers for the higher strings may have invited laziness of the fingers. However, the register difference could have been due to a difference between the left and right hands. In fact, this is the interpretation Repp (1995) proposed for the register effect he found on the digital piano. In the present case, this interpretation seems less plausible. A separate analysis on the four pianists for whom hand information was available showed a significant effect of register within hands [$F(1,3)=15.01$, $p<0.04$] but not of hand/register [$F(1,3)=4.23$, $p<0.14$]. A separate analysis on the middle-register KOTs likewise did not show a significant hand difference overall [$F(1,3)=0.71$]. Individually, two pianists had significantly longer KOTs for the right rather than the left hand, one showed a nonsignificant difference in the opposite direction, and one showed no difference. All four, however, showed significant effects of register. This suggests that there was an effect of register apart from any hand differences, although consistent differences in favor of the right hand in the other five pianists could have contributed to the overall magnitude of the register effect.

The other main effect shown in Fig. 8 is that of position in the sequence or pairs of fingers [$F(7,56)=7.18$, $p<0.0001$]. This pattern, which was shown by all pianists but one, again matches earlier findings on the digital piano: Regardless of the hand used, KOTs decreased in the course of an upward or downward movement on the keyboard and were "reset" to a longer duration after the direction of the sequence had reversed. This effect interacted with register [$F(14,112)=2.53$, $p<0.004$], mainly because it was more pronounced at higher than at lower pitches. However, it did not interact significantly with step size or, in the separate analysis on four pianists, with hand.

Three additional interactions reached significance in the overall ANOVA. Position interacted with cycles [$F(14,112)=2.42$, $p<0.006$], due to a tendency towards longer KOTs at the beginning of the first and at the end of the last cycle within a sequence.[12] Cycles were not involved in any other significant effects. The other two significant effects were a triple interaction between position, step size, and register [$F(28,224)=1.69$, $p<0.02$] and a two-way interaction between register and IOI [$F(4,32)=4.31$, $p<0.007$]. These interactions were primarily due to scaling of effects: For example, effects of register were largest at the longest IOI, and effects of IOI were largest in the high register.

Individual differences in average KOT were very large, with a range from 23 to 185 ms. Short KOTs were shown not only by the author, who as an amateur does not have a refined legato technique, but also by the two most advanced graduate student pianists. The longest KOTs, presumably reflecting the best legato technique, were exhibited by two female undergraduate pianists. A point of considerable interest is that the variability of individual pianists' KOTs increased roughly in proportion to their average KOT; this relationship is shown in Fig. 9. The measure of variability shown is the standard deviation (the root mean square) of the five-way

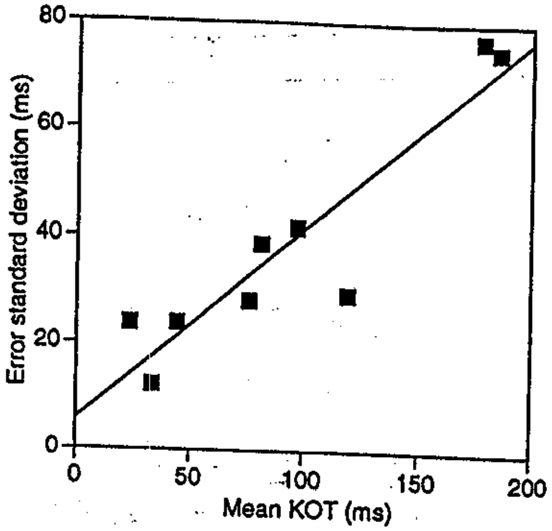

FIG. 9. Variability of KOTs as a function of average KOT duration for individual pianists, with the best-fitting linear regression line.

(cycles×register×IOI×step size×position) interaction in each individual ANOVA. The relationship is reminiscent of analogous findings regarding the precision of IOI timing in finger tapping (e.g., Peters, 1989) and expressive piano performance (Repp, in press), but the KOTs are much shorter than the IOIs for which a generalized Weber's law holds.

Because the variance between cycles was much smaller than that between pianists, many interactions that were nonsignificant in the overall ANOVA reached significance in the analyses on individual pianists' data. However, it would lead too far to discuss these idiosyncratic patterns. One of the two advanced graduate students' data deserve attention, however, because he was the only individual who had also participated in the digital piano study about two years earlier. His average KOT on the digital piano was 34 ms, compared to 23 ms on the Yamaha. His average KOT patterns as a function of position were similar. He showed no effect of step size in either experiment, and his IOI main effect was restricted to an increase in KOT at the slow tempo. In both studies, this pianist showed an interaction between IOI and step size, with a systematic tempo effect only at the 1-st separation. The pattern of his position by step size interaction was also replicated, despite the different black/white key patterns involved in the two studies.[13] Only a paradoxically reversed main effect of register in the earlier study was not replicated here. These observations indicate that individual patterns of KOTs may exhibit some stability over time and across different instruments.

IV. *LEGATO* ARTICULATION IN A SIMPLE MUSICAL PIECE

The present study included the performance of a short piece of music requiring *legato* articulation. The purpose of collecting these additional data was to see whether some of the findings of the preceding experiment would hold up in a simple but meaningful musical context. The music chosen allowed comparison of KOTs between the two hands, although they were confounded with register (about one octave apart), and comparison between two note values (IOIs). The modulation of KOTs in the course of the music as a function of position in a phrase and of fingering was of interest, as were individual differences among the pianists in average KOT.

A. Method

After playing the scales and *arpeggi* just discussed, the nine pianists sight-read an easy piece requiring *legato* articulation. The composition was *Dialogue*, No. 3 from the *Little Piano Book* of Vincent Persichetti. In this music, shown in Fig. 10, the left and right hands alternate playing a melody consisting of quarter notes and eighth notes while the other hand plays a simple chordal accompaniment. The right-hand melody is almost entirely within the fourth octave; that of the left hand is mostly in the third octave. The melody is divided into seven 2-bar phrases, four for the right hand and three for the left. All but one of these phrases are subdivided by slurs in the original score, but, in order to minimize breaks, the pianists were asked to disregard the original slurs and play each phrase with continuous legato; a single large slur across each phrase was drawn by hand in the score, as shown in Fig. 10.[14] In order to standardize the fingering as much as possible, fingering suggestions were also entered into the score, though it was not possible to verify that they were followed precisely. The suggested tempo was 120 beats per minute, and a silently flashing metronome was in view. The intended IOIs thus were about 250 ms (eighth notes) and 500 ms (quarter notes). Several pianists played at a somewhat slower tempo. Use of the pedal was not permitted. After a brief familiarization with the music, each pianist played the piece three times on the Yamaha Disklavier and was recorded in MIDI format. KOTs were computed for the melodic voice in each phrase, and KOTs at phrase boundaries were ignored.

B. Results and discussion

The KOTs across the positions in the music constitute a "KOT profile." There were very large individual differences among the pianists' profiles, which means that an average KOT profile must be regarded with caution. Nevertheless, short of displaying all individual profiles, it seems most convenient to discuss the data in this way. The average KOT profile is shown in Fig. 11. Rectangles represent the overlaps at the onsets of quarter notes, squares those at the onsets of eighth notes. Dotted vertical lines separate the seven phrases.

The majority of the KOTs (the mode of the distribution of average KOTs, as it were) was in the vicinity of 50 ms. There were a few shorter and a larger number of longer values. The very long KOTs usually represent the average of extremely long KOTs exhibited by some pianists and "normal" KOTs shown by others in these positions. Extremely long KOTs reflect "finger pedaling," a key depression that extends during the whole duration of the following note and sometimes beyond. For example, the G4 at the beginnings of bars 11 and 12 was held by some pianists through the following E4. This is a perfectly acceptable technique if the successive notes are consonant, as they are in this case. Finger pedaling was much more common in pianists who had

FIG. 10. *Dialogue*, No. 3 from the *Little Piano Book* of Vincent Persichetti (© 1954 Elkan-Vogel, Inc.). Reproduced with permission of the publisher (Theodore Presser Company, Bryn Mawr, PA). Long slurs, fingerings, and measure numbers have been added to the score by the author.

relatively long average KOTs, such as the two female undergraduate students mentioned earlier.

Some of the very short KOTs represent grouping within phrases. For example, the very short KOT in the middle of the second phrase occurs at the half-phrase boundary. The shortest KOTs in the fourth and seventh phrases seems to have a different reason, the preparation of a shift in hand position.

Bars 1, 3, 7, and 9 contain similar melodic patterns in quarter notes, and they all show similar KOT patterns as well: A longer KOT occurs on the fourth beat (the third data point in Fig. 11), which means that the quarter note on the third beat was prolonged. At the beginnings of bars 2, 4, 8, 10, and 14 there are linearly ascending or descending sequences of four eighth notes. They consistently show a longer KOT for the second note, which means that the first note was prolonged. Both of these tendencies may be consequences of metrical stress: The prolonged notes are in metrically accented positions. To determine the reliability of these observations, separate repeated-measures ANOVAs were performed on these quarter-note and eighth-note data. Both trends were significant [$F(3,24)=8.74$, $p<0.001$, and 7.15, $p<0.002$, respectively], though not every individual pianist exhibited them.

Given the wide range of average KOTs, there does not appear to be a systematic difference between KOTs for eighth and quarter notes, analogous to the effect of IOI in the preceding experiment. Of course, the different IOIs were intermixed here. Nor was there any obvious difference between the right hand (phrases 1, 3, 4, and 6) and the left hand (phrases 2, 5, and 7), at least as far as the shorter KOTs are concerned. This was also true for individual pianists. Very

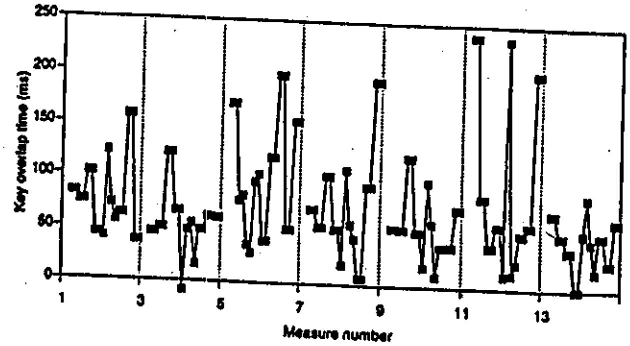

FIG. 11. Average KOTs within the phrases of the Persichetti piece. Squares represent KOTs at the onsets of eighth notes, rectangles KOTs at the onsets of quarter notes.

long KOTs (finger pedaling), however, occurred almost exclusively in the right hand.

Individual differences in average KOT among the pianists were largely preserved: The correlation between their individual average KOTs for tone sequences with IOIs of 500 ms and their median KOTs in the present performances (which seemed preferable over mean KOTs in view of the finger pedaling) was 0.79 ($p<0.01$).

In general, these data were too variable to reveal simple effects comparable to those observed with the tone sequences. However, the KOT patterns point to structural and ergonomic factors that may come into play in more complex musical materials: phrase boundaries, metrical accents, shifts in hand position, and fingering patterns. These factors deserve more thorough study in future investigations.

V. GENERAL DISCUSSION

A. Piano acoustics

The acoustic analysis part of this study, while mainly serving to characterize the tones used in the subsequent perception and production experiments, does make a modest contribution to the piano acoustics literature which contains relatively little information on the relative sound levels of tones, their decay times (especially after release), and their variability. It should be emphasized that the absolute levels and decay times, as well as their specific patterns of variability as a function of pitch, are specific to the instrument and the recording conditions. However, the data do indicate some general trends and the magnitude of acoustic variability to be expected in a grand piano.

There is a very regular relationship between MIDI velocity and the peak sound level of piano tones, which is well described by a negatively accelerated quadratic function (Fig. 1). Palmer and Brown (1991), in an analysis of tones recorded from a computer-controlled Bösendorfer SE grand piano, found a linear relationship between hammer velocity (in m/s) and peak sound amplitude, which implies a logarithmic relationship between hammer velocity and peak sound level (in dB). The relationship between hammer velocity and MIDI velocity then would also have to be logarithmic in order for the present results to agree with theirs. Indeed, the author found this to be the case on a similar Bösendorfer instrument which had been interfaced with a standard MIDI system, so that both hammer and MIDI velocities could be obtained.[15] If a similar relationship between hammer and MIDI velocities held on the Yamaha Disklavier used here (and there is no particular reason to doubt this, though the hammer velocities were not known), then the present findings are indeed consistent with those of Palmer and Brown.

The present measurements replicate Repp's (1993) finding that the peak sound levels of different piano tones recorded in the same location vary over a range exceeding 10 db, almost half the dynamic range of the instrument (Fig. 2). Importantly, however, there is now also evidence that the specific pattern of these variations varies with the location of the recording microphone.[16] Although careful studies of the perceived loudness of natural piano tones remain to be conducted, it is clear that they do not sound as uneven dynamically as their peak sound levels might suggest, despite the fact that the listener occupies a specific position in space. Although it remains to be shown that a shift in microphone position as small as the distance between a listener's ears can change this pattern of variation significantly, it seems quite possible that binaural hearing and small head movements largely smooth out these unsystematic differences in peak sound level (cf. Benade, 1976, p. 347).

The measurements of the prerelease decay of 1-s piano tones confirmed the well-known fact that high tones decay faster than low tones (Martin, 1947). In addition, they revealed a fairly abrupt discontinuity at the beginning of the fifth octave (C5). Lower tones decayed at a steady rate that increased with pitch, from about 10 to 20 db/s. Higher tones decayed at a much faster rate over the first few hundreds of milliseconds and then at a slower rate beset with irregularities. These irregularities are attributed to beats among slightly mistuned multiple strings (Hundley *et al.*, 1978). The strings of lower tones presumably take longer than 1 s to get out of phase (cf. Martin, 1947), so that the stage of slower and more irregular decay was not reached in the 1-s tones measured here. Martin (1947) has described the two-stage decay of lower tones, but he reported only a single decay rate for higher tones, perhaps because his time resolution was too coarse. Given the observations on string interactions and coupling by Hundley *et al.* (1978) and Weinreich (1990), there is no particular reason why high tones should differ from low tones in that respect; only their strings get out of phase more rapidly, so that the initial fast decay extends only over a few hundred milliseconds. What remains surprising is the abruptness of the change in decay patterns around C5 in the present data.

The acoustic property most pertinent to *legato* articulation, and the one most neglected in previous literature, is the postrelease (damped) decay rate of the piano tones. It was generally between 50 and 120 dB/s, which means that damped tones of high intensity took 0.5 to 1 s to decay completely (i.e., by 60 dB, according to conventional standards). These times probably reflect the reverberation time of the room the instrument was situated in; they may be even longer in a large hall but shorter in an anechoic environment. However, there was also considerable variation from tone to tone, and damped 250-ms tones decayed more quickly than longer tones, for reasons that are not fully understood. It was not determined whether the pattern of variations in decay rate varied with microphone position.

Even though the postrelease decay rates measured here may be room-specific, they represent an important characteristic of the tones heard by the participants in the subsequent experiments. Especially relevant is the fact that the decay rates were considerably slower than those of the digital piano tones used in Repp (1995).

B. Perception of *legato* articulation

Given this difference in postrelease decay rates, it was surprising to find that listeners in the perceptual experiment chose *longer* KOTs in this study than in the previous one. This was true not only for optimal and maximal *legato*, but also for minimal *legato*, which is essentially a gap detection task. One might have expected gaps to be more difficult to detect when the postrelease decay rate of the tones is slower, but in fact they seemed easier to detect. In some conditions, there was not even a nominal gap (i.e., a negative KOT) associated with minimal *legato* adjustments. Similarly, one might have expected acoustic overlap of successive tones to become noticeable at shorter KOTs when there is a slower and longer postrelease decay. It appears that the perception of connectedness among successive tones is not a simple function of their acoustic contiguity and overlap. Exposure to a realistic piano timbre and room acoustics may have affected listeners' perceptual criteria in the direction of greater tolerance for the sonorities of briefly overlapping tones.

As predicted, listeners' tolerance for acoustic overlap increased as the relative consonance of successive tones increased and as their pitch register increased. The register effect may be due to the increase in decay rate with pitch, but it could also represent a reduction of perceived dissonance among higher tones, due to their fewer and more widely spaced harmonics. To the extent that the second explanation applies, the effect of register may be similar to that of pitch step size. The perceptual roughness accompanying a dissonance may make acoustic overlap more detectable.

The present data, in conjunction with those of Repp (1995), suggest that there is a nonmonotonic relationship between tempo (IOI duration) and the KOT judged to be optimal for legato. Listeners tolerate less overlap at short IOIs (<500 ms) but also show reduced KOTs at long IOIs (>800 ms). This reduction at long IOIs runs counter to the smaller acoustic overlap of long tones, due to their progressive decay. Therefore it must have a different cause. One possibility is that the rhythmic coherence of successive tones begins to be weakened at IOIs of 1000 ms, whose rate is almost twice as slow as that of the preferred pulse or tactus (Parncutt, 1994). Perceptual integration of the "heads" and "tails" of decaying tones into unitary temporal forms and consequent perceptual segregation of overlapping tones seems to underlie listeners' remarkable tolerance for (and indeed, failure to perceive) simultaneities extending over hundreds of milliseconds. At long IOIs, this temporal integration may begin to weaken, so the acoustic overlap of the "tails" of tones with the "heads" of following tones may become more noticeable.

C. Production of *legato* articulation

A comparison of the present production data with those of Repp (1995) would seem to be relevant to the issue of pianists' adjustment to different instruments and acoustic environments. Precise comparisons are difficult because of the different individuals involved and the large individual differences in average KOT within each group. Nevertheless, the finding that the average KOTs were similar on the real piano and on the digital piano, even though the postrelease decay times differed by a factor of 2, suggests that *legato* technique is not very flexible in response to extramusical factors. While small adjustments (detectable only in a within-pianist comparison) may well occur, pianists' general motor habits seem to be fairly well entrenched. Indeed, it is very difficult for someone who typically plays legato with short KOTs (such as the author) to produce long KOTs, and while pianists who have acquired this *legatissimo* technique through long practice may be able to play with short KOTs, they are unlikely to abandon the fruit of their hard labor unless the music specifically requires it. Basically, it seems that a characteristic individual *legato* style is maintained regardless of the specific acoustic conditions.

The effects of tempo and step size on KOTs replicate earlier findings on the digital piano. The tempo effect is likely to have a kinematic cause (increased general tension and/or earlier preparation for finger lifting at faster tempi), especially since the increase in KOTs from medium to slow tempo contradicts the decrease observed in the perceptual task. The step size effect, too, could be kinematic in origin (spread of fingers), though it is tempting to conclude that its cause is aesthetic, due to relative consonance. While the direction of the effect agrees with that found in perception, there was little difference in production between the 1-st and 2-st conditions, which clearly differed in perception. The reason for this discrepancy is not clear.

Only the effect of register was free of kinematic influences, though it was partially confounded with possible hand differences which, unfortunately, could be assessed in only some of the pianists. Nevertheless, there was an indication of an independent effect of register on KOTs which parallels a similar effect in perception and may reflect a compensatory adjustment to the more rapid decay of high tones. In addition, some pianists seem to play somewhat more *legato* with the right than with the left hand, and "finger pedaling" occurred almost exclusively in the right hand.

One of the most consistent findings on the digital piano, the dependence of KOT on position in the tonal sequence, was fully replicated here. It suggests that KOT is a contextually modulated parameter that may carry structural and expressive information within the *legato* range. This result is the one most deserving of follow-up investigation with more varied musical materials. A small step in that direction was taken here by examining the KOTs in performances of Persichetti's *Dialogue*, in which unexpectedly large variability of KOTs was encountered, due in part to finger pedaling by some pianists. Future studies may have to employ somewhat more controlled materials in order to determine more precisely the structural and ergonomic factors that influence KOT. One likely factor is the distance between keys in conjunction with fingering, and future research on *legato* articulation may dovetail nicely with ongoing work on pianists' fingering strategies (e.g., Parncutt *et al.*, in press).

ACKNOWLEDGMENTS

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[1]This is sometimes referred to as finger legato, since the same effect can be achieved by holding and releasing the first tone with the damper pedal. The present study does not deal with legato achieved through pedaling.

[2]A baby grand piano of the same make was used in the perception experiment. The change in pianos was beyond the author's control. Acoustic recordings were made from the baby grand piano as well but only partially analyzed, as they were found to contain some distortion.

[3]Nominal durations are given as specified in the MIDI instructions. Due to a peculiarity of the MAX software, however, the actual durations were 3.9% longer than specified.

[4]Decay times are usually given in terms of the time it takes for the sound level to drop by 60 dB. However, the dynamic range of the present recordings was only about 40 dB, so that conventional decay times could not be measured directly.

[5]The difference in absolute sound level between the instruments is meaningless.

[6]Repp (1995) found a decrease in the peak intensity of digital piano tones in the highest (sixth) octave, but this may have been an artifact of using a fixed 30-ms integration window.

[7]On the present Yamaha Disklavier, C2–G2 were double-stringed, while all pitches from G#2 on were triple-stringed.

[8]These are the actual durations. The intended intervals had been multiples of 250 ms, but their actual durations turned out to be 3.9% longer, due to the MAX software.

[9]As pointed out earlier, the later replacement of the instrument was not under the author's control. Since the lid of the piano had been removed by other users and could not easily be put back, the experiment was run without the lid on. The acoustic conditions thus were not identical with those described in the previous section: Both the instrument and the listeners' distance from it were different. Arguably, however, the acoustic characteristics of the tones heard by the listeners were more similar to those of the Yamaha grand piano than to those of the digital piano in Repp's (1995) study.

[10]Repp (1995) called the position factor "pairs of fingers." The pairs of fingers are 1-2, 2-3, 3-4, 4-5, 5-4, 4-3, 3-2, 2-1 for the right hand and 5-4, 4-3, 3-2, 2-1, 1-2, 2-3, 3-4, 4-5 for the left hand; that is, 1-2 in the right hand is aligned with 5-4 in the left hand, and so on. Therefore "position in the sequence" seems a better name for this factor.

[11]In order to be able to determine later whether a middle-register sequence had been played with the right or the left hand, it was necessary to record the random sequence in which the music sheets were presented to each pianist. Unfortunately, this step was omitted for the first five pianists. This oversight was embarrassing but not fatal, as hand differences were only of secondary interest.

[12]There may also have been longer IOIs in these positions, reflecting traces of expressive timing. (No analysis of IOI durations was conducted.)

[13]While the 1-st sequences were comparable (WBWBW; W=white, B=black), the 3-st sequence was WBBWW on the digital piano but BWWBB on the Yamaha.

[14]One pianist, contrary to instructions, followed the slurs in the original score and thus showed large negative KOTs (i.e., breaks) at several points within phrases. These KOT values were excluded from the data, as were a few isolated instances of large negative KOTs in other pianists' data. The pianist was also excluded from the analysis of variance.

[15]The precise function was $MV=52.3+45.7\ln(HV)$, where MV =MIDI velocity and HV=hammer velocity. The relationship between hammer velocity and peak sound level was also logarithmic. (Unpublished data collected in the course of a study by Repp, 1993.) It is not obvious why peak sound level should be a quadratic function of MIDI velocity, but quadratic functions fit the data in Fig. 1 distinctly better than do logarithmic functions.

[16]This was also found in similar measurements conducted on tones recorded from the baby grand piano used in the perception experiment.

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