Acoustics, perception, and production of *legato* articulation on a digital piano

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This study investigated the perception and production of *legato* ("connected") articulation in repeatedly ascending and descending tone sequences on a digital piano (Roland RD-250s). Initial measurements of the synthetic tones revealed substantial decay times following key release. High tones decayed faster than low tones, as they did prior to key release, and long tones decayed sooner than short tones because of their more extensive prerelease decay. Musically trained subjects (including pianists) were asked to adjust the key overlap times (KOTs) of successive piano tones so that they sounded optimally, minimally, or maximally *legato*. The results supported two predictions based on the acoustic measurements: KOTs for successive tones judged to be optimally or maximally *legato* were greater for high than for low tones, and greater for long than for short tones, so that auditory overlap presumably remained more nearly constant. For minimal *legato* adjustments the effect of tone duration was reversed, however. Adjusted KOTs were also longer for relatively consonant tones (three semitones separation) than for dissonant tones (one semitone separation). Subsequently, KOTs were measured in skilled pianists' *legato* productions of tone sequences similar to those in the perceptual experiment. KOTs clearly increased with tone duration, an effect that was probably motoric in origin. There was no effect of tone height, suggesting that the pianists did not immediately adjust to differences in acoustic overlap. KOTs were slightly shorter for dissonant than for consonant tones. They also varied with position in the ascending–descending tone sequences, indicating that the pianists exerted strategic control over KOT as a continuous expressive dimension. There were large individual differences among pianists, both in the perceptual judgment and in the production of *legato*.

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INTRODUCTION

A. Modes of articulation

On most musical instruments, successive tones can be produced in two basic modes of articulation: unconnected and connected. In the unconnected mode, perceptible intervals of (what seems to be) silence separate successive tones. On the piano, this is achieved by releasing a key before the next key is depressed. It is appropriate whenever the score indicates a rest or *staccato* articulation, and also at the ends of phrases or slurs as an aspect of "phrasing." The connected mode is generally referred to as *legato* articulation. Here the preceding tone seems to end at the same time as the following tone begins. Correspondingly, the pianist releases a key at about the same time as the next key is depressed.

The piano is one of a number of instruments that permit the simultaneous sounding of several tones. This is achieved by depressing several keys at the same time.[1] The possibility of this third mode of articulation, the simultaneous or chordal mode, has implications for *legato* articulation: In order to achieve a very smooth connection between tones, a pianist may release a key after depressing the key for the following tone, so that there is a small amount of overlap. The duration of this overlap (time of key release minus time of key depression for the following tone) will be referred to as *key overlap time* (KOT) in the following; it is positive when there is overlap, and negative when the key release precedes the following key depression.[2]

A small amount of key overlap is not perceived as a simultaneity but rather as an increased connectedness of the tones. One reason why some amount of key overlap can be tolerated is that the sound level of a piano tone, after a rapid rise, decays as a function of time, so that the end of the preceding tone is usually much softer than the beginning of the following tone. Because of this discrepancy in relative intensity and the abrupt rise time of the following tone masking may occur, so that a brief acoustic overlap may not be readily detectable.

However, masking is not likely to provide a full explanation because the acoustic overlap of successive piano tones is actually much more extensive than suggested by the KOT. Although the damper extinguishes the string vibrations when a key is released, this process is not instantaneous, and soundboard vibrations and acoustic reverberation in a room may further contribute to prolonging a tone's acoustic duration. The highest piano strings (usually starting with F$^{\#}$6) do not have any dampers at all. Thus when two tones are perceived as unconnected (i.e., when KOT is negative), the apparent silent interval between them is at least partially filled by the decaying energy of the first tone, and there may in fact be some acoustic overlap. In typical *legato* articulation, where one key is released shortly after the depression of the next key, the acoustic overlap may be quite substantial, yet listeners do not complain about hearing simultaneous tones. This is probably due to auditory grouping of a tone's "tail" with its "body," and consequent perceptual segregation of

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the simultaneous tones, within limits (see Bregman, 1990).[3] Here we note only that a short KOT corresponds to a much longer *tone overlap time*, whose precise duration depends on the intensities and decay rates of the tones and on the ambient noise level.

These considerations give rise to a number of interesting questions about the acoustics, perception, and production of *legato* articulation on the piano—questions that the present study was intended to address in a preliminary way:

(1) *Acoustics*: What are the decay characteristics of piano tones, particularly after key release?

(2) *Perception*: How much key overlap (and consequent tone overlap) can listeners tolerate when judging the articulation of successive tones to be *legato*, before they start hearing simultaneities? Does experience as a pianist affect these judgments? What factors influence the amount of key overlap listeners are willing to tolerate?

(3) *Production*: What are the typical KOTs when pianists play *legato*? Is there variation among individual pianists in this respect? Do pianists vary their timing of key depressions to compensate for factors that affect perceptual overlap? Are there differences in degree of *legato* between pianists' right and left hands, and between pairs of fingers on each hand?

There is not much previous research addressing these questions; what little is known to the author is summarized in the following sections.

B. Acoustics

The acoustic decay characteristics of sustained (undamped) piano tones are fairly well understood (see, e.g., Martin, 1947; Hundley *et al.* (1978); Weinreich, 1990; Wogram, 1990). After a brief rise time and early amplitude peak, the sound decays slowly, typically with an initial faster rate of decay giving way to a slower rate. These two decay rates result from several factors including vertical and horizontal string motion: The vertical component is initially larger but is transmitted to the vertically moving soundboard and hence decays to below the level of the horizontal component within a few seconds. The decay rate can be altered radically, however, by interactions among the two or three strings struck by the same key (initially in phase but not so later), and by the relative impedance of the soundboard at the vibrating frequencies. Tones above roughly 700 Hz (about *F*5) seem to have only a single decay rate (Martin, 1947). The fact most relevant to the present study is that the decay rate increases with fundamental frequency: While a low tone such as C2 takes about 4 s to decay by 20 dB (1/10 of the amplitude) on an upright piano, C4 takes only about 2 s, and C6 about 1 s (Wogram, 1990). Because of the complex resonance characteristics of the soundboard and other factors, however, the decay rates of tones close in pitch may differ substantially (Benade, 1990; Wogram, 1990). The precise decay characteristics of individual piano tones thus are largely instrument specific and need to be measured in any particular experimental context.

The literature offers surprisingly little information about the decay characteristics of piano tones following key release, after the damper falls upon the strings. These *postrelease decay times* are likely to depend on the amplitude of string vibration when the damper touches the strings, on the thickness of the strings, on the weight and surface condition of the damper, and on the velocity of key release (damper lowering), among other things. Moreover, the postrelease decay times of tones heard by a listener are probably a good deal longer than those of the strings alone, since they include the decay of (undamped) soundboard vibrations and reverberation. Therefore it is necessary to measure these times in any specific setting used for research purposes. In the first part of the present study, this was done on the output of an electronic instrument whose sounds presumably had been modeled on a specific piano recorded under specific conditions. The main concern here was not the representativeness of these measurements for pianos in general but an adequate characterization of the specific acoustic environment in which the following perception and production experiments were conducted.

C. Perception

In the large literature on auditory psychophysics, there does not seem to be a single study that investigated listeners' ability to detect the acoustic overlap between the end of one tone and the beginning of another tone. However, there are many studies on the detectability of a silent gap between two pure tones or noise bursts (e.g., Perrott and Williams, 1971; Williams and Perrott, 1972; Collyer, 1974; Fitzgibbons *et al.*, 1974; Divenyi and Danner, 1977; Neff *et al.*, 1982; Shailer and Moore, 1983; Buus and Florentine, 1985; Formby and Forrest, 1991). Unfortunately, none of these studies employed complex tones with decaying amplitudes; amplitude envelopes were rectangular, and gap detection thresholds were generally on the order of a few milliseconds. Many studies have shown that the gap detection threshold increases as the frequency separation of two pure tones increases, and Dannenbring and Bregman (1976) have reported perception of illusory overlap when alternating nonoverlapping tones are sufficiently different in frequency to be allocated to separate auditory streams. The intensity of the sounds seems to have no effect on gap detection, except at very low levels. However, Plomp (1964) demonstrated in a widely cited study that the gap detection threshold increases as the relative sound level of the second of two noise bursts decreases. He attributed this finding to a decay of auditory sensation following the offset of the first noise. This internal decay, in terms of equivalent sound-pressure level (dB), was a negative exponential function of time and reached the sensation threshold 225 ms after noise offset, regardless of noise intensity. That is, the internal decay time was constant, but the decay rate varied with sound level.

Plomp's results are cited here to acknowledge that a sound often does not end with its acoustic termination; if its acoustic offset is abrupt, it continues to resonate for some time in the listener's auditory system. When a sound decays over time, however, the physical input generally will determine the auditory sensation, since acoustic decay (in dB) generally is a linear rather than negative exponential function of time (Benade, 1990). Thus, unless the acoustic decay rate is very high, the sensation level due to internal decay of auditory input will generally be below the momentary input level. For this reason (and others), the psychoacoustic literature is not very helpful in predicting what degree of acoustic overlap of piano tones might lead listeners to judge them as connected (*legato*) or unconnected. Even a controlled psychoacoustic study with ramped complex tones and highly trained listeners would only provide a partial answer. The question is best addressed within the realistic sound environment of piano tones, using listeners with musical experience rather than extensive laboratory training.

A recent study by Kuwano *et al.* (1994) moved in that direction. In the initial, more psychoacoustic part of their research, they synthesized a 13-note melody with sounds whose pressure envelopes were either rectangular or triangular (i.e., linearly decaying).[4] The melody was presented at a fixed tempo, and the overlap of the tones was varied by changing their total duration. Musically untrained subjects judged when the tones changed from "separated" to "connected," and from connected to "overlapping." The average tone overlap times corresponding to these two boundaries were −56 and 16 ms for steady-state tones but 30 and 104 ms for decaying tones. That is, listeners judged steady-state tones to be optimally connected when they had a brief silent gap between them, whereas decaying tones perceived as connected overlapped by 67 ms, on the average. Apparently, this overlap was not heard as such.

In the second, more realistic part of their study, Kuwano *et al.* asked a pianist to play the tune on an electronic piano in eight different ways, ranging from "markedly separated" to "extensively overlapping," while keeping the tempo constant. The recordings were subsequently presented to listeners who judged them as "separated," "marginally connected," or "overlapping." Their responses confirmed the pianist's intentions: The performance intended to be marginally connected (i.e., *legato*) also received the highest number of judgments in that category. The average overlap time of successive tones in that performance was 240 ms.

Kuwano *et al.* calculated overlap times by reproducing the tones of the pianist's performances individually on a MIDI system and measuring the point at which each tone had decayed to 60 dB below its peak level; this point was taken to be the end of the tone, and its distance from the onset time of the originally following tone was the overlap time.[5] Although this −60-dB criterion is commonly adopted in measuring reverberation times and, according to Benade (1990), often corresponds to the threshold of audibility for decaying isolated sounds, it may be a rather liberal criterion for tones in context, as the final part of the decaying tone is probably masked by the following tone. Still, in the absence of an independent investigation of masking among piano tones, the estimate of acoustic overlap of *legato* tones provided by Kuwano *et al.* is the best currently available. Although the overlap times of tones judged connected were much shorter in their first experiment, for reasons that are not quite clear, their second experiment is more representative of actual piano performance.

D. Production

Key overlap times have been measured in several studies of piano performance, though none of them focused specifically on *legato* playing. Thus Sloboda (1983) showed that pianists vary KOTs (i.e., articulation) to convey different metrical interpretations of the same sequence of notes.[6] In a follow-up study, Sloboda (1985) displayed frequency distributions of KOTs for two pianists playing two tunes. The distributions were bimodal, with one peak around 40 ms and the other somewhere between −100 and −220 ms, corresponding to *legato* and *staccato* modes of articulation, respectively.

KOTs were also measured by MacKenzie and Van Eerd (1990) in a study of rapid scale playing at several tempi. When the tempo was 8 tones per second or faster, average KOTs were 5 ms or less; the longest times (28 ms) were observed at the slowest tempo (4 tones per second). KOTs were about twice as long for the right hand as for the left hand; however, this difference was confounded with register, as the two hands played two octaves apart. Rapid scale playing is not conducive to optimal *legato* articulation, but neither does it permit *staccato*; thus these data may be representative of "minimal" *legato*.

Palmer (1989) reported KOTs, even though she defined overlap acoustically as "the overlapping time of two adjacent notes' amplitude envelopes" (p. 335). Since she used a synthesizer with tones that had a fixed 80-ms decay following key release, and since she averaged KOTs across a number of tones varying in articulation, her data are not very revealing from the present perspective. More relevant are average KOT profiles for ten pianists playing simple tunes, presented by Drake and Palmer (1993). Maximum KOTs were between 0 and 50 ms, presumably reflecting *legato* articulation. This study also included an analysis of a concert pianist's performance of an excerpt from a Beethoven sonata, but the KOTs were not reported in detail. Interestingly, both Palmer (1989) and Drake and Palmer (1993) found that the KOT was shorter when one of the two tones, especially the first one, was relatively long.

The situation most conducive to *legato* playing, short of providing explicit instructions, is the expressive performance of a slow, melodious piece. Repp (1994, in press) selectively measured KOTs in two pianists' performances of Schumann's "Träumerei." One pianist (an amateur) generally showed KOTs around 0 ms, whereas the other pianist (a professional musician) showed surprisingly long KOTs, often of several hundreds of milliseconds. Since her performances did not sound abnormal, such extreme overlaps are evidently acceptable to the ear in an expressive performance of complex music, but they may represent an extreme case.[7]

E. The present study

The production data available so far suggest that *legato* articulation is most often associated with KOTs of 0–50 ms, though longer overlaps may be observed under some circumstances. None of these measurements were obtained in a situation in which pianists were instructed to play *legato*. Little attention has been given to acoustic tone overlap and to listeners' perceptual tolerance for such overlap, with the exception of the pioneering study by Kuwano *et al.* (1994). The present research took an approach similar to theirs, but it focused in more detail on the acoustic characteristics of the tones used and on several factors that may influence KOTs. The study included an acoustic analysis, a perceptual experiment, and a production experiment.

The purpose of the acoustic analysis was to describe the decay characteristics of the digital piano tones used in the subsequent experiments. The analysis was expected to confirm the known fact that high piano tones decay more rapidly than low tones before the key is released. Therefore the postrelease decay times were expected to be shorter for high tones than for low tones. One question of interest was whether the postrelease decay times reflect merely a tone's sound level at the moment of key release, or whether there are also differences between high and low tones in their postrelease rates of decay.

In the perceptual experiment, the method of adjustment was used to obtain judgments of optimal and marginal *legato* from musically trained listeners, including pianists. The stimuli were scales and *arpeggi* varying along three dimensions: tempo, register, and interval step size (correlated in this instance with relative dissonance versus consonance of successive tones). It was predicted that more key overlap would be tolerated at slow tempi and in a high register, because long and high tones are softer at key release than are short and low tones, so that acoustic overlap is both less extensive and less audible. Listeners' sensitivity to these factors may reflect perceptual constancy in terms of some criterion of auditory tone overlap. It was also expected that more key (as well as acoustic) overlap would be tolerated with relatively consonant sequences of tones than with relatively dissonant ones, both for auditory and aesthetic reasons. Because of the higher commonality of partials of consonant complex tones (Kameoka and Kuriyagawa, 1969), their acoustic overlap may be less detectable as well as more pleasing to the ear than the overlap of dissonant tones.

In the production experiment, skilled pianists provided samples of their best *legato* by playing the scales and *arpeggi* used in the perception experiment. The question was whether they would adjust their KOTs in response to factors that affect acoustic overlap, or whether *legato* playing is motorically invariant and insensitive to these factors, even though they may influence perceptual judgments. (This hypothesis will be further qualified below.) Secondary questions concerned the existence of individual differences in KOTs, as well as possible differences between the left and right hands and among pairs of adjacent fingers.

I. DECAY CHARACTERISTICS OF THE DIGITAL PIANO TONES USED

The purpose of the acoustic analysis was to characterize the sound-pressure envelopes of the piano tones used in the perception and production experiments, with particular attention to the decay following key release. The analysis was essential because the tones were produced by an electronic instrument about whose sound inventory no detailed specifications were available from the manufacturer. A previous study (Repp, 1993) had focused on their peak sound levels and on aspects of their spectral structure but had not considered their decay characteristics.

It would have led too far to investigate in detail the extent to which these synthetic piano tones were representative of natural piano tones. However, it seemed highly likely that they were modeled on a set of acoustically recorded tones. Thus their decay probably represented not only the decay of string vibrations but also the decay of soundboard vibrations and acoustic reverberation in some enclosed space. This was as it should be because it corresponds to what a listener hears and because it makes the synthetic tones sound realistic, especially over earphones.

A. Method

The instrument was a Roland RD-250s digital piano using a proprietary "adaptive synthesis" algorithm. "Piano 1" sound was used with a constant MIDI velocity of 40, because this velocity was also used in the subsequent perception experiment.[8] To reduce the number of measurements, only every third tone was analyzed in the range from C2 (65 Hz) to C7 (2093 Hz). Four series of tones between these two endpoints were played under the control of a Macintosh IIvx computer, using the PERFORMER MIDI sequencing program. The four series differed in the *nominal tone duration*, i.e., in the interval between MIDI "note on" (key depression) and "note off" (key release) commands, which was 250, 500, 750, or 1000 ms. The nominal intertone interval (between each MIDI note off command and the next note on command) was 500 ms.[9]

The analog output of the digital piano was input to a Macintosh IIci computer using AUDIOMEDIA software with a sampling rate of 44.1 kHz. The digitized waveforms were then analyzed using SIGNALYZE software. The rms amplitude envelope was computed for each tone using a window size of 30 ms. Since the program does not display dB values, all measurements were performed on the rms amplitude values and subsequently converted into dB (with an arbitrary reference). As the output of the digital piano was deterministic and temporal resolution was very fine, it was not necessary to perform each measurement more than once. Apparent irregularities were double-checked, however.

B. Results and discussion

Figure 1 shows *prerelease decay* as a function of musical pitch, as measured in the 1000-ms tones. The graph shows each tone's peak rms level, as well as the sound levels 250, 500, 750, and 1000 ms from energy onset.[10] Peak level was reached after a variable rise time, which ranged from 24 to 43 ms for C2 to C5 (except for A4, which had an unusually slow rise time of 89 ms) but was much shorter (around 5 ms) from E^{b}5 on.[11] Peak levels were fairly stable between C2 and C6, although there was some variation from tone to tone (as already demonstrated by Repp, 1993). Above C6, peak level decreased as a function of pitch. The initial prerelease decay also increased dramatically at high pitches. Tones below C6 decayed by only a few dB over the first 250 ms, whereas from C6 on there was a very substantial initial decay. Beyond 250 ms, the decay rates varied less dramatically

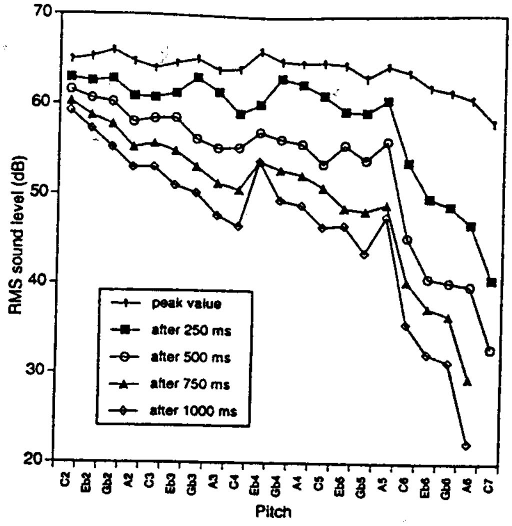

FIG. 1. Prerelease decay: Relative rms sound levels of digital piano tones at their peaks and at four time points in their amplitude envelopes (measured from energy onset).

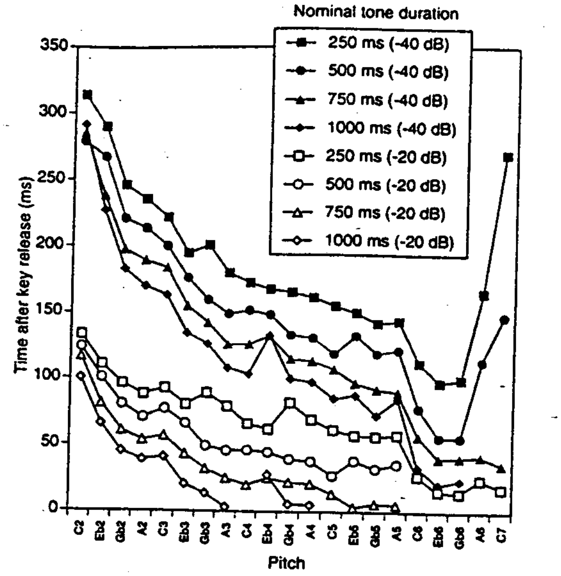

FIG. 2. Postrelease decay times: Time after key release by which the tones had decayed to −20 and −40 dB of their peak level.

as a function of pitch, except for the tones in the lowest octave, which decayed at a much slower rate. Some individual tones (e.g., E♭4, A5) had amplitude envelopes with irregular characteristics, which may reflect beats caused by slightly mistuned strings in the original piano that served as a model. The sound level of C7 beyond 500 ms was too low to be measured. It is clear from Fig. 1 that the prerelease decay increased with pitch, as expected, though there were irregularities in this relationship which presumably reflect the complex acoustics of real pianos.[12]

The four lower functions in Fig. 1 represent the sound levels at the time of key release for the four tone durations employed here. Since this sound level decreased as pitch increased and as tone duration increased, the *postrelease decay time* must likewise have decreased with increasing pitch and increasing duration. This is confirmed in Fig. 2, which shows how soon after key release tones of different nominal durations reached 1/10 (−20 dB) or 1/100 (−40 dB) of their peak amplitude.[13] Missing data points indicate that the specified level was reached before key release. The postrelease decay times were quite substantial. Even by the conservative −40-dB criterion, the lowest tones took about 300 ms to decay, and tones up to C6 took at least 100 ms. Tones above C6 decayed somewhat sooner, though A6 and C7 were abnormal in that they showed much slower decay when released early than when released late. The reason for this anomaly was not clear, as these tones should not have been affected at all by key release because of the absence of dampers for the highest strings in a real piano.

The effects of prerelease decay on the postrelease decay time, shown in Fig. 2, would have been obtained even if the *postrelease decay rate* had been constant. However, higher-pitched tones also decayed faster than lower tones, not only before but also after key release. Prerelease tone duration, on the other hand, did not seem to have any systematic effect on postrelease decay rate; therefore Fig. 3 shows the data averaged over the four nominal tone durations. The figure shows the time it took for the postrelease sound level to decay by 20 dB. (This is the time difference between the −20- and −40-dB points in Fig. 2.) This time decreased from about 180 to 90 ms over the pitch range investigated (i.e., the decay rate increased from about 11 to 22 dB/cs), and the decrease as a function of pitch was much steeper during the lowest octave than during the higher octaves. The points for the two highest pitches have been omitted in the figure because of their much slower postrelease decay rates (cf. Fig. 2). The lines were fitted by hand to indicate the general trend of the data; again, there are some irregularities.[14]

Although there seem to be no data in the literature to compare the present results with, the complex and somewhat irregular acoustic characteristics of the present tones suggest that they were indeed modeled after acoustically recorded piano tones. It should be noted, however, that natural piano tones exhibit much greater variation in peak sound level (Repp, 1993); some kind of equalization must have been applied in the proprietary synthesis scheme that generated the digital tones. To what extent the present findings are representative of the decay characteristics of natural piano tones

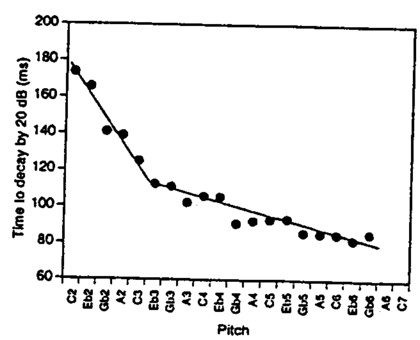

FIG. 3. Postrelease decay rates: The time it took for tones to decay by 20 dB following key release.

remains to be determined. However, they adequately describe the acoustic environment within which the following experiments were conducted.

II. PERCEPTUAL JUDGMENT OF *LEGATO* ARTICULATION

The purpose of this experiment, as already indicated, was to investigate the influence of three factors (register, tempo, and relative consonance) on the amount of key overlap perceived as *legato*. An adjustment task was used to determine the overlaps judged to represent the "best" as well as "minimal" and "maximal" *legato*. It was expected that listeners would tolerate more key overlap in conditions where there is less acoustic overlap due to shorter postrelease decay times, namely in the high register and at a slow tempo (long tone durations). Furthermore, it was predicted that more key (and acoustic) overlap would be tolerated for relatively consonant than for dissonant tones. (The consonant tones were also more widely separated in pitch, which could lead to the same prediction.) Half of the musically trained subjects were pianists, and it was of interest whether their specific experience would be reflected in different criteria for, and/or reduced variability of, their adjustments.

A. Method

1. Subjects

Fourteen paid volunteers participated. All but one were Yale undergraduates; they ranged in age from 18 to 25. All subjects were musically trained, having received between 8 and 15 yr of formal instruction on at least one instrument. Seven were pianists (though several of them played a second instrument as well); the others played various instruments including violin, cello, double bass, oboe, trumpet, and guitar.

2. Materials and procedure

An interactive adjustment task was set up using the Roland RD-250s digital piano interfaced with a Macintosh IIvx computer. The control program was written using the MAX graphic programming environment. The program created various random orders of 24 tone sequences resulting from the combination of three registers, four tempi, and two step sizes (or degrees of relative consonance). All tones had a constant MIDI velocity of 40. Each sequence consisted of a continuously ascending and descending scale or *arpeggio* based on five different tones. The three registers (low, medium, high) represented starting frequencies of C2 (65 Hz), C4 (262 Hz), and C6 (1047 Hz), respectively. The four tempi represented tone interonset intervals (IOIs) of 260, 519, 779, and 1039 ms.[15] The two step sizes were 1 and 3 semitones (st), so that the tone sequences represented either a short chromatic scale extending over 4 st (a major third) or a diminished-seventh-chord *arpeggio* extending over 1 oct. Tones separated by 1 st formed the highly dissonant interval of a minor second, whereas tones separated by 3 st formed the moderately consonant interval of a minor third. Sequences were started and stopped by clicking START and STOP "buttons" on the computer screen. Nominal tone duration (key release time, and hence also KOT) was controlled by a horizontal "slider" on the screen that could be dragged or clicked with the mouse. Each sequence started with the slider in the leftmost position, corresponding to a nominal tone duration of 150 ms, which made the tones sound definitely unconnected. Nominal tone durations controlled by the slider ranged from 150 to 1500 ms in 10-ms steps; they were not displayed numerically.

Subjects sat at the computer and listened binaurally to the output of the digital piano over Sennheiser HD540II earphones. The volume was set at the same comfortable level for all subjects. After receiving written instructions and a few minutes of free practice, subjects completed four blocks of 24 trials each, with short breaks in between. Each block was initiated by the experimenter who reset the program, which then generated a new random sequence of the same 24 trials. The current trial number was displayed on the computer screen. The subject initiated each trial by clicking the START button and terminated it by clicking the STOP button after adjusting the slider according to the criterion specified. The program stored the slider settings, and the experimenter saved them in a file at the end of each block. Each block took between 10 and 15 min to complete.

Instructions were different for each of the first three blocks. In the first block, the subject was asked to adjust the slider so as to find the best *legato*. (S)he was advised to move the slider slowly to the right until the tones sounded not only connected but unacceptably overlapping, and then to reverse direction and try to "zero in" on the optimal *legato* setting by moving the slider back and forth over a narrower region. (S)he was warned not to "overshoot" the target zone on the slider when the tempo was fast.[16] In the second block, the subject was asked to zero in on the boundary between unconnected and connected tones, and to find the setting that was just barely acceptable as *legato* (minimal *legato*). In the third block, the subject was asked to find the highest (rightmost) setting that was still acceptable as *legato*, before the tones started to sound noticeably overlapping (maximal *legato*). The fourth block replicated the first, the task being again to find the best *legato*.

3. Data analysis

KOTs were determined by subtracting the IOI durations from the nominal tone durations adjusted by the subjects. In a few instances of overshoot, where the KOT exceeded the IOI (indicating that the subject was oblivious to the complete overlap of successive tones), the IOI was subtracted once again, yielding the KOT of tones separated by one intervening tone. Twelve missing data points (the program occasionally failed to save the last trial in a block) were replaced by the group mean for that particular condition. Repeated-measures analyses of variance were conducted on the data from each block, with the three independent variables (IOI, register, step size) as within-subject factors, and with pianistic expertise as a between-subject factor.

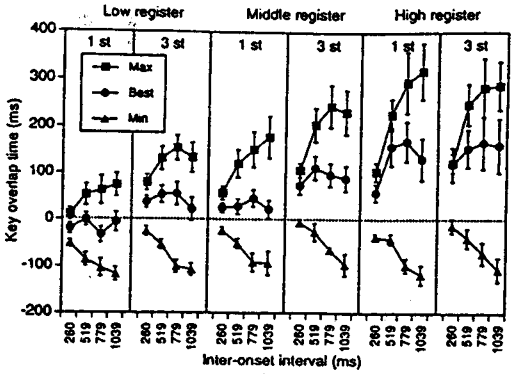

FIG. 4. Adjusted KOT in three conditions as a function of register, step size, and IOI. The bars represent plus/minus one standard error.

B. Results and discussion

The results are summarized in Fig. 4. Consider first the best *legato* adjustments, which are shown averaged over blocks 1 and 4. There was substantial between-subject variability. (Note that standard errors are shown, not standard deviations.) The variability increased with register, step size, and IOI. Nevertheless, there were a number of reliable effects. First, as predicted, KOT increased with register [$F(2,24)=25.52$, $p<0.0001$]; the average KOTs were 14, 62, and 139 ms, respectively. Second, also as predicted, KOT increased as a function of step size or relative consonance [$F(1,12)=20.96$, $p<0.0007$]; the averages were 48 and 95 ms for 1- and 3-st step sizes, respectively. The effect of step size was reduced in the high register, which was reflected in a two-way interaction [$F(2,24)=3.65$, $p<0.05$]. Third, there was also a main effect of IOI [$F(3,36)=3.57$, $p<0.03$], though it was smaller and nonmonotonic; the respective average KOTs were 49, 84, 83, and 70 ms. The nature of the IOI effect varied with both register and step size; the triple interaction was significant [$F(6,72)=2.43$, $p<0.04$]. Two additional significant effects were the main effect of blocks [$F(1,12)=6.59$, $p<0.03$], due to shorter KOTs (by 20 ms) in block 4 than in block 1, and the block by step size interaction [$F(1,12)=5.42$, $p<0.04$], due to a reduced step size effect in block 4. Variability was also reduced in block 4. Pianistic expertise had no effect at all.

The results for maximal *legato* judgments were basically similar, except that the adjusted KOTs were longer and the effect of IOI was stronger and more nearly monotonic. Variability was very high and increased with register and IOI, though not with step size. The effect of register was pronounced [$F(2,24)=21.45$, $p<0.0001$], with average KOTs of 87, 162, and 235 ms, respectively. The predicted effect of step size (or consonance) was present [$F(1,12)=8.91$, $p<0.02$], though not very large; the average KOTs were 137 and 185 ms, respectively. The step size effect was again absent in the high register, although the two-way interaction fell short of significance. The effect of IOI was highly significant [$F(3,36)=19.20$, $p<0.0001$], due to a negatively accelerated increase in KOT with IOI (80, 164, 198, and 204 ms, respectively). There was a significant IOI by register interaction [$F(6,72)=3.71$, $p<0.003$], due to larger effects of IOI as register increased. There was no effect of pianistic expertise.

Adjustments of minimal *legato* exhibited much less variability. The average KOTs were negative, indicating that nominal gaps of up to 100 ms can still be acceptable as *legato*, depending on the condition. The most striking effect here was that of IOI [$F(3,36)=25.22$, $p<0.0001$], though it was inverted: KOT *decreased* (i.e., nominal gap time increased) as IOI increased, the average durations being −26, −50, −89, and −107 ms, respectively. There was also a significant effect of step size [$F(1,12)=9.40$, $p<0.01$] in the predicted direction, with average KOT being less for chromatic scales (−76 ms) than for diminished-seventh-chord *arpeggi* (−60 ms). Finally, there was an effect of register [$F(2,24)=3.85$, $p<0.04$], though it was not monotonic: KOTs were shortest for low tones (−81 ms) and longest for medium-pitched tones (−57 ms), with high tones in between (−66 ms). No other effects reached significance.

From Fig. 4 it is clear that the *range* of KOTs acceptable as *legato* increases dramatically with IOI and with register. Since several degrees of connectedness are probably discriminable within the larger ranges (though the relevant perceptual experiments remain to be conducted), the results imply that the slower the tempo and the higher the register, the greater the variety of possible *legato* nuances. The opposite effects of IOI on the upper and lower boundaries of the *legato* range probably account for the irregular effect of IOI on best *legato* judgments, which lie approximately in the center of the range in the low and middle registers, but closer to the upper boundary in the high register.

The effect of IOI on maximal *legato* judgments was as expected, with increasing KOTs being tolerated as IOI increased. This is almost certainly due to the lower sound levels at release and the shorter postrelease decay times of long tones, which result in reduced acoustic and auditory overlap with the following tone. It is noteworthy that the IOI effect was largest between 250 and 500 ms and smallest or absent between 750 and 1000 ms. This agrees with the faster initial decay of piano tones, which takes place during the first 500 ms or so (see Fig. 1).

The strong effect of register for both best and maximal *legato* judgments was also in the predicted direction, with the largest KOTs in the high register and the smallest in the low register. This is consistent with the much faster decay of high than low tones, both before and after key release. Unlike the effect of IOI, the register effect was of similar magnitude in best and maximal *legato* judgments.

The predicted effect of step size was obtained for both best and maximal *legato* judgments, but it was virtually absent in the high register. This interaction is compatible with an interpretation in terms of relative consonance. The relative dissonance of complex tones has been attributed to the interaction of individual partials (Plomp and Levelt, 1965; Kameoka and Kuriyagawa, 1969), and since high piano tones have fewer significant partials than low tones, they are likely to show fewer such interactions and hence smaller effects of perceived dissonance. It is difficult to see how such an interaction could have arisen from fundamental frequency separation alone. The fundamentals of tones separated by 3 st were well within the auditory filter bandwidth (Moore and Glasberg, 1983) in the low register but were separated by more than one critical band in the high register, whereas frequencies separated by 1 st were always within the same critical band. If anything, this should have led to a larger step size effect in the higher register.

The minimal *legato* judgments essentially represent gap detection thresholds. Of course, these estimates are much less precise than those obtained in typical psychoacoustic experiments, but their ecological validity may be greater. It is interesting to note that the average adjustments never corresponded to a key overlap, not even for high tones whose rapid prerelease decay caused a substantial drop in sound level before the onset of the following tone. Moreover, even though this drop increased with tone duration, more rather than less of a nominal gap was needed to hear a separation between long tones, and this was true regardless of pitch, the effect of register being rather small and nonmonotonic. Thus it was not the case that a sufficiently large drop in the amplitude envelope disrupted perception of connectedness. Rather, it seemed as if long tones sounded inherently more *legato* than short tones, so that more of a physical separation was required to hear them as disconnected. Although Kuwano *et al.* (1994) did not investigate the effect of nominal tone duration on perceptual judgments, their measurements of acoustic overlap times in a pianist's production show longer overlaps for long than for short tones when the intention was to play with various degrees of connectedness or overlap, but also longer acoustic gaps for long than for short tones when the intention was to play in a disconnected mode.[17] This pattern seems congruent with the present perceptual findings of an increased range of KOTs for long tones and of an inverted effect of tone duration (i.e., IOI) on nominal gap durations.

Kuwano *et al.* (1994) did not report KOTs but only acoustic overlap times, based on a −60-dB criterion for the end of a tone. According to that measure, the acoustic overlap was less than 170 ms when listeners gave predominantly "separated" responses, about 240 ms when they judged the tones to be "marginally connected," and more than 280 ms when they gave mostly "overlapping" responses. The IOIs were 600 and 300 ms (Kuwano, personal communication; the test melody contained both quarter and eighth notes), the pitch steps varied between 2 and 5 st, and the pitches ranged from F4 to F5. The present 260- and 519-ms IOI conditions in the middle register with a 3-st step size come closest to their stimuli. The average postrelease decay time to −60 dB (extrapolated from the −20- and −40-dB points in Fig. 2) of the relevant tones is roughly 250 ms. This implies acoustic overlaps of about 230 ms for minimal *legato*, 340 ms for best *legato*, and 400 ms for maximal *legato*. If the "marginally connected" category of Kuwano *et al.* is equated with the present minimal *legato*, then the data seem in agreement. It seems, however, that the present best *legato* stimuli would have been judged by their listeners as overlapping, and the present maximal *legato* stimuli, as extensively overlapping. There are a number of differences between the studies, however, that could account for this apparently lower tolerance for overlap in their subjects, such as their use of musically untrained subjects. Also, their piano tones may have had decay characteristics different from those of the present tones; unfortunately, they did not describe those characteristics.

On a more general level, the present data agree with their findings in demonstrating that a substantial acoustic overlap can be tolerated by listeners before they complain about simultaneity of pitches. However, the results should not be taken to imply that the overlap is not detectable as such, even though the end of the "tail" of the decaying tone is almost certainly masked by the more powerful following tone. To assess the auditory detectability of overlap and the masking between simultaneous complex tones, precise psychoacoustical experiments are required. What matters more than detectability in a musical context, however, is perceptual and aesthetic tolerance within a specific instrumental environment and an associated performance tradition.

Because of masking between and/or perceptual segregation of simultaneous tones, it seems unlikely that any perceptual criterion (either best or maximal *legato*) corresponds to a fixed amount of acoustic overlap. This possibility was explored briefly by adding the postrelease decay times determined in the first part of this study to the KOTs found in the second part. As expected, there was no constancy overall, though low-pitched tones judged to be maximally *legato* all overlapped by about the same amount. The listeners' responses in the adjustment task may be taken as *prima facie* evidence for some *auditory* constancy in terms of degree of connectedness. However, there may be no simple acoustic correlate of this constancy.

A final word is in order about individual differences. There was no difference between experienced pianists and nonpianists, but there was large variability within each group. The most unusual subject was a guitarist whose adjusted KOTs were all negative, even for maximal *legato*. Apparently, he was acutely sensitive to acoustic tone overlap and employed a criterion appropriate for his own instrument. Of course, he contributed strongly to the variability among the nonpianists. But even when his data were excluded, there was no clear difference between the two groups, and pianists themselves apparently had widely divergent criteria for what counted as a good *legato*. This may be related to individual differences in average KOT during *legato* articulation, an aspect of a pianist's "touch." The final part of this study investigated this production aspect of *legato* playing.

III. PRODUCTION OF *LEGATO ARTICULATION* BY *PIANISTS*

The purpose of this experiment was twofold. One aim was to measure the KOTs pianists produce when they intend to play optimally *legato* and to assess the magnitude of individual differences, as well as possible differences between right and left hands and between pairs of fingers. The second aim was to investigate whether pianists adjust, consciously or subconsciously, to factors that affect acoustic tone overlap and perceptual judgments of *legato* style, as demonstrated in the previous experiment. The pianists were asked to play scales and *arpeggi* like those used as stimuli in Sec. II, on the same instrument. Thus they were operating under similar acoustic conditions, and even though the sounds were synthetic and the keyboard felt different from that of a real piano, it was expected that, if adjustments in *legato* playing occur in response to acoustic factors on a real piano, they would also occur on a digital piano.

The same three factors as in Sec. II were varied in the materials, and the predictions were the same: Pianists were expected to show longer KOTs in a high register than in a low register, at a slow tempo (long IOIs) than at a fast tempo (short IOIs), and in a relatively consonant than in a dissonant sequence of tones. A complicating circumstance, however, was that these factors, tempo and step size in particular, may also have purely motoric consequences that are independent of the auditory feedback about tone overlap. Thus it seems that a smooth *legato* is more difficult to achieve (and perhaps also aesthetically less desirable) at a fast than at a slow tempo; if so, this effect reinforces the prediction based on acoustic considerations, but results supporting the prediction then cannot be attributed to a single cause. The situation is different with regard to step size: It may be more difficult to achieve a smooth *legato* when the fingers are spread (3-st step size) than when they are close together (1-st step size); if so, this effect counteracts the predicted effect of relative consonance, so that attribution of an obtained effect to acoustic–aesthetic or motoric causes is possible. Only a change of register seems to have no obvious motoric implications, as long as each hand stays within its typical range on the keyboard. Thus an effect of register on KOT would provide the best evidence for an adjustment to acoustic conditions.

Individual differences among pianists in average KOT were of interest because they may reflect an aspect of the elusive quality of touch. Since in much music the right hand plays the melody and the left hand the accompaniment, it was also considered possible that *legato* style is better developed in the right hand, leading to longer KOTs. As noted in the Introduction, MacKenzie and Van Eerd (1990) observed such a hand difference in rapid scale playing, but the fact that the right hand played in a higher register was not controlled for. In the present design, to avoid awkwardness, the low register was played only with the left hand, and the high register only with the right; however, the middle register was assigned to either hand, thus making a direct comparison possible. Finally, it was hypothesized that there might be more overlap between the "weak" fourth finger and its neighbors than between the more independent first three fingers.

A. Method

1. Subjects

The subjects were eight highly skilled pianists. Four of them (all female) were graduate students at the Yale School of Music; three (all male) were seniors in Yale college and, as winners of the annual undergraduate concerto competition, had performed as soloists with the Yale Symphony Orchestra; one (female, older than the others) was a semiprofessional accompanist. They were paid for their participation.

2. Materials

The materials were very similar to those used in experiment 1, except that they were shown in musical notation on separate sheets of paper. Each scale or *arpeggio* ascended and descended three times and ended on a long note. The step size was 1 or 3 st, and the starting pitch was C2, C4, or C6. Two identical versions were prepared for the middle register, one marked "with the left hand" and the other "with the right hand." The low register examples were to be played with the left hand, and the high register examples with the right hand. Three tempo conditions were indicated by the note values: sixteenth notes, eighth notes, or quarter notes. All examples were to be played at about 60 beats per minute, so that the tempi corresponded to IOIs of approximately 250, 500, and 1000 ms, respectively.

3. Procedure

The subject sat at the Roland RD-250s keyboard and listened to its output over Sennheiser HD540II earphones. A metronome flashing silently at 60 beats per minute stood within view. After presenting written instructions and permitting a brief warm-up period on the instrument, the experimenter placed the randomly shuffled 24 music sheets before the pianist, one at a time. (S)he was asked to play each example "with (her or his) best *legato*" at the tempo indicated but not exactly with the metronome; expressive timing and dynamics, to the extent that the simple materials encouraged them, were welcome. The overall dynamic level asked for was *mezzoforte*. The fingering was prescribed in the instructions as 5-4-3-2-1-2-3-4-5 for the left hand and 1-2-3-4-5-4-3-2-1 for the right hand.[18] The experimenter monitored the playing of all examples to make sure that the instructions were followed. If either the subject or the experimenter was not satisfied with an example, it was repeated immediately. All productions were recorded in MIDI format using PERFORMER software.

4. Data analysis

KOTs were calculated and subjected to repeated-measures analyses of variance. Three separate analyses were conducted: on the left-hand data, on the right-hand data, and on the middle register data for both hands. The factors in these analyses were step size (two levels), IOI (three levels), register or hand (two levels), fingers (eight levels), and repetitions (three levels), with subjects as the random factor yielding the interactions that served as error terms. Note that the fingers factor (i.e., pairs of fingers: 5-4, 4-3, 3-2, 2-1, 1-2, 2-3, 3-4, 4-5 for the left hand, and 1-2, 2-3, 3-4, 4-5, 5-4, 4-3, 3-2, 2-1 for the right hand) was not decomposed into finger pairs (four levels) and order of fingers within each pair (two levels), for reasons that will become evident. The repetitions factor was treated as crossed with the other factors, not as nested within examples. Analogous ANOVAs were also performed on each individual pianist's data, in which case repetitions served as the random factor.

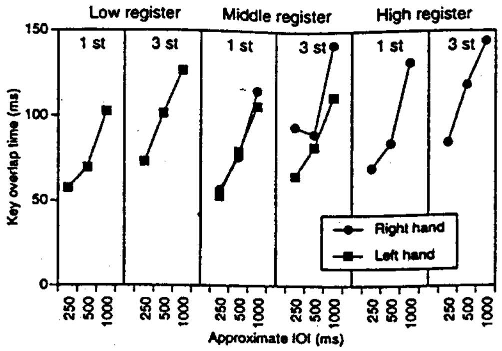

FIG. 5. *Legato* production: Average KOT as a function of IOI, step size, register, and hand.

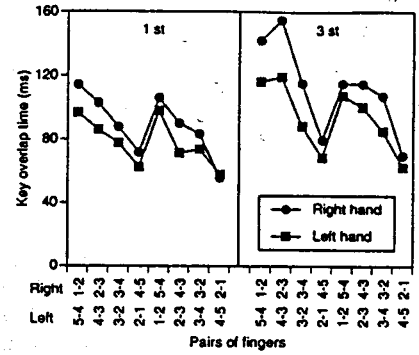

FIG. 6. *Legato* production: Average KOT as a function of finger pair, step size, and hand.

B. Results and discussion

The main results, averaged across pianists, repetitions, and fingers, are shown in Fig. 5. The average KOTs ranged from about 50 to 150 ms across the different conditions. The most striking effect was that of IOI, which was significant in all three analyses [left hand: $F(2,14)=7.93$, $p=0.005$; right hand: $F(2,14)=9.68$, $p<0.003$; both hands: $F(2,14)=9.47$, $p<0.003$]. KOTs increased as the tempo decreased, as was predicted on both acoustic and motoric grounds.

There was also an effect of step size or relative dissonance: KOTs were slightly longer for diminished-seventh-chord *arpeggi* than for chromatic scales [left hand: $F(1,7)=4.14$, $p<0.09$; right hand: $F(1,7)=21.76$, $p<0.003$; both hands: $F(1,7)=15.11$, $p=0.006$]. The effect was reliable only for the right hand, and in the middle register there was a significant interaction between hand and step size [$F(1,7)=5.71$, $p<0.05$]. Since there is no obvious motoric reason why *arpeggi* should be played more *legato* than chromatic scales, the step size effect probably reflect an adjustment to the relative consonance or dissonance of the successive tones. The greater sensitivity of the right hand to this dimension may be due to its leading role in melodic material.[19]

There was no significant effect of register for either hand. Although it seems that more overlap occurred in the high than in the low register, this difference may be due to hands rather than register. The absence of a register effect indicates that the pianists did not adapt their *legato* technique to the acoustic decay characteristics of the tones. The effect of IOI may then also be motoric rather than perceptual in origin.

There was a significant effect of hand in the middle register [$F(1,7)=6.82$, $p<0.04$]. KOTs were longer for the right hand (101-ms average overall) than for the left hand (86 ms). Although seven of the eight pianists showed a difference in this direction, it was individually reliable for only three. Note also that, in the middle register, the hand difference was apparently restricted to the *arpeggi*.

As expected, there were striking individual differences in average KOTs. Individual grand averages ranged from 27 to 145 ms. There was no obvious relation to either gender or relative experience of the pianists. Although experienced pianists can undoubtedly change their degree of *legato* when the music requires it, the fact that they produced such different KOTs in the same experimental situation suggests genuine individual differences in *legato* technique or touch.[20]

The final effect to consider is that of fingers, which is portrayed in Fig. 6. It was highly reliable [left hand: $F(7,49)=7.86$, $p<0.0001$; right hand: $F(7,49)=13.15$, $p<0.0001$; both hands: $F(7,49)=12.93$, $p<0.0001$] and was shown by every pianist. Its pattern was not what had been expected, however. Rather than reflecting longer KOTs for less independent pairs of fingers, it represented an interaction between finger pairs and order or, more simply, a main effect of position in the scale or *arpeggio*: In each upward movement *and* in each downward movement, KOTs started out long and then decreased until the scale or *arpeggio* reversed direction. This decrease was fairly linear in scales but apparently nonlinear in *arpeggi*. The finger by step size interaction was significant for the right hand [$F(7,49)=4.10$, $p<0.002$] and for both hands [$F(7,49)=7.68$, $p<0.0001$]; for the left hand, the triple interaction with register was significant instead [$F(7,49)=3.36$, $p<0.006$]. Although the two hands are shown separately in Fig. 6, the interaction of fingers with hand was not significant.

The consistency of the finger effect indicates that it represents an important aspect of *legato* articulation, though its exact cause is uncertain at present. One possibility is that the forearm rotates as the scale or *arpeggio* is being played, transferring weight from one part of the hand to the other; this larger-scale movement may lag behind the fingers, causing decreased key overlap when moving in a given direction. Another factor that could contribute to the relatively short KOT just before a reversal is that the same finger must be used twice in close succession (2-1-2 or 4-5-4). However, there was no finger by IOI interaction, which would be expected if anticipatory lifting of a finger played an important role. Another possible factor that apparently can be ruled out is dynamic variation. The pianists naturally tended to increase the dynamic level as they went up and to decrease it as they went down a scale or *arpeggio*. While the absolute and especially the relative sound levels of successive tones could have an influence on the perception and production of KOTs, note that the obtained parallel trends for the ascending and descending halves (Fig. 6) is contrary to the opposite trends expected on the basis of dynamics. Most likely, therefore, the finger effect, like the tempo effect, is not perceptual but rather motoric or cognitive in origin.

IV. GENERAL DISCUSSION

The present study combined acoustic analyses, perceptual judgments, and production measurements in an attempt to obtain some basic information about *legato* playing. Stimulated by the recent demonstration by Kuwano *et al.* (1994) that tones played and judged to sound connected show considerable acoustic overlap, the present study extended the investigation to focus on several factors that influence the amount of this overlap.

The acoustic analyses demonstrated that the postrelease decay times of piano tones decrease as pitch (register) increases and as the duration of the tone increases. These effects are due in part to prerelease decay, which is faster for high than for low tones and more extensive for long than for short tones, and in part to an increase in postrelease decay rate with pitch (but not with duration). This information, previously unavailable in systematic form in the literature, led to the prediction that listeners would adjust their perceptual criteria in judging *legato* articulation, and that pianists would adjust their *legato* playing, so as to avoid extensive acoustic overlap. That is, KOTs (the directly observable variable in MIDI recordings) were expected to be longer for tones with shorter postrelease decay times (i.e., high and long tones).

These predictions were confirmed in the perceptual experiment, which was really a study of "passive" *legato* production, without involvement of the fingers. Listeners' adjustments were evidently sensitive to acoustic overlap, with KOTs being longer for high and long tones. Whether perceptual constancy in terms of some criterion of auditory (non)overlap was maintained across conditions could not be demonstrated directly, but it may be assumed that the subjects aimed for such a constancy, as this was essentially what the instructions requested them to do. It would be naive to expect a simple measure of acoustic overlap to correspond to such a perceptual constancy, but application of dynamic models of auditory processing may uncover an invariant auditory property in future research.

The results of "active" *legato* production were different. Although KOTs were longer for long than for short tones, this may be attributed to motoric factors. There was no effect of register; what seemed like one was probably due to a difference between hands. Thus pianists' playing seemed to reflect primarily motoric constraints, not adjustments to varying acoustic overlap. This implies, paradoxically, that the pianists' intended best *legato* might be judged by listeners (even by themselves!) to be nonoptimal in certain conditions, for example, at a slow tempo in the low register (compare Figs. 5 and 4). A perceptual evaluation of the recorded natural *legato* samples remains to be conducted. It should be noted that, unlike the stimuli in the perception experiment, the natural productions varied in timing and dynamics, and in KOT from one tone pair to the next.[21] These kinds of natural variation may well have an effect on the perceptual criterion for what constitutes a good *legato* in a melody.

There was one factor that both passive and active *legato* players were sensitive to: When the successive tones were relatively dissonant (1 st apart), adjusted and produced KOTs were shorter than when the tones were relatively consonant (3 st apart). Although, in principle, pitch separation *per se* could have been responsible for this difference, the effect was attributed to relative consonance on grounds of plausibility.[22] However, the effect may not be purely aesthetic in nature: Due to the larger number of shared harmonics of relatively consonant tones, there may be greater masking and/or fusion between consonant than between dissonant tones (see DeWitt and Crowder, 1987), making acoustic overlap more difficult to detect. There was also a confounding of step size with pitch range, and hence with average pitch and average acoustic overlap: On the average, *arpeggi* had slightly shorter overlaps than chromatic scales because they covered a 1-oct range, whereas the latter extended only over the first 4 st in this range. More detailed investigations will be required to sort out these variables.

Palmer (1989) and Drake and Palmer (1993) reported that KOTs tended to be shorter when one of two successive tones was relatively long, especially the first one. This observation seems to contradict the clear tendency toward longer KOTs for longer tones in the present study. However, their finding was obtained in materials containing both short and long tones, and their pianists were not instructed to play *legato* throughout. Most likely, their finding reflects the fact that long tones tend to end motives and phrases; the reduced KOT following such tones is an aspect of "phrasing" which was absent in the present homogeneous materials, unless the progressive reduction in KOT during the ascending and descending portions of the scales and *arpeggi* is to be interpreted in a similar manner.

MacKenzie and Van Eerd (1990) observed longer KOTs for the right hand than for the left hand in rapid scale playing. The present production data, obtained at much slower tempi, tend to support their interpretation of this effect as one of hand, rather than of register. It appears that, in some pianists at least, the right hand is more adept at playing *legato* than the left hand.

The absolute KOTs reported here are longer than those obtained in most earlier studies. This is probably due to the relatively slow tempi and to the explicit instruction to play *legato*, though it is also possible that the Roland RD250s keyboard, with its relatively easy action, encouraged an increased *legato*. Certainly, replications and extensions of the present findings on a real computer-monitored piano are desirable, together with measurements of the postrelease decay times of natural piano tones.

The relative insensitivity of the present pianists to acoustic/perceptual factors should not be interpreted as implying that pianists cannot adjust their degree of *legato* when musical circumstances require it. On the contrary, they are likely to be quite flexible in that regard. Kuwano *et al.* (1994) demonstrated that a pianist can play with different degrees of connectedness or separation when instructed to do so, though their results look somewhat categorical, with little difference in acoustic overlap between tones intended to be "marginally connected," "overlapping a little," and "overlapping to some degree." However, these terms are nearly synonymous and may have been so understood by the pianist. Whether there is a tendency to perceive or produce *legato* in a categorical fashion is an interesting question for future research, as are the many factors that may affect KOT, such as fingering, phrasing, and individual style. All expressive parameters of music performance are subject to continuous and systematic modulation, and KOT is hardly an exception. However, it is a little studied aspect of piano technique, and much remains to be learned about it.

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[1]Alternatively, the damper pedal may be engaged while depressing keys successively. The present study, however, was not concerned with pedaling.

[2]The technique of "partial release," which is possible on grand pianos, will not be considered here.

[3]Sonoko Kuwano (Namba *et al.*, 1992) has pointed out that the overlap is distinctly audible as an "impurity" at the onset of an isolated tone excerpted from a *legato* passage. Note the parallel to the perception of coarticulation in speech (e.g., Fowler, 1984).

[4]The spectral composition of the sounds was not reported.

[5]Although they failed to mention this in their published paper, Kuwano *et al.* did include the original key release when playing back the individual tones (Kuwano, personal communication). Thus they had information about postrelease decay times as well as about KOTs, but only acoustic tone overlap times were reported.

[6]Sloboda seemed to be unaware of the postrelease decay of piano tones, as he stated that "This event [i.e., release of the key] is simultaneous with the termination of the sound" (p. 383).

[7]Extreme *legato* is also referred to as *legatissimo* or "finger pedaling." Nearly continuous use of the damper pedal in these performances further increased the acoustic overlap of tones and may also have increased the tolerance levels of listeners.

[8]On the Roland RD-250s, the spectral characteristics of the tones change with key velocity (intensity), as they do on a real instrument (cf. Repp, 1993). The choice of the fixed velocity value was arbitrary.

[9]The author is striving toward a consistent terminology of musical events. *Nominal tone duration* refers to the MIDI level of description and should be distinguished from (*actual, acoustic*) *tone duration*, which includes the postrelease decay time, and from *note duration* (better: *note value*) which is not a physical magnitude at all but refers to the relative values (integer ratios) of notated symbols, such as 1/4 or 1/8.

[10]Since the onset of energy in the amplitude envelope started 15 ms (half the duration of the integration window) before the onset of energy in the waveform, these measurement points correspond to 235, 485, 735, and 985 ms, respectively, from energy onset in the waveform.

[11]The rise time was the time from the onset to the peak of the amplitude envelope, minus 30 ms. This estimate was reasonably accurate because of the fast rise and slow decay of the energy. A signal with zero rise time and no decay (i.e., a step function) would have a rise time of exactly 30 ms (the window duration) in the rms amplitude envelope.

[12]In fact, preliminary analyses of acoustically recorded piano tones suggest that their decay characteristics are even more irregular than those of the synthetic tones analyzed here.

[13]These times, too, were adjusted for the window duration by subtracting 30 ms from the times measured in the envelope. Resolution of amplitude values was not fine enough to determine the −60-dB points, which had been used as the criterion of tone offset by Kuwano *et al.* (1994). However, those time points can be extrapolated from the differences between the −20- and −40-dB time points (see also Fig. 3), assuming that the postrelease decay (in dB) was linear.

[14]Very similar results were obtained when, instead of taking the difference between the −20- and −40-dB time points relative to peak sound level, the time to decay by 20 dB was measured relative to the sound level at key release. Additional measurements showed that an increase in key velocity from 40 to 60 increased this decay time by about 10 ms regardless of pitch, but a further velocity increase from 60 to 80 had no effect. Key velocity varied in the *legato* production experiment, reported below.

[15]The intended IOIs were 250, 500, 750, and 1000 ms. However, when the sound output was later digitized and measured, it was discovered that the IOIs were consistently too long by 3.9%, due to an unrecognized problem with the MAX software. This problem did not affect the accuracy of timing: The standard deviation of IOIs within the same sequence was less than 1 ms, probably representing just human measurement error. The nominal tone durations (key release times) were not affected either.

[16]Overshoot was possible (and did occur on a few trials) because the range of the slider was fixed; thus fast tone sequences required an adjustment in the lower (left-hand) region of the slider, whereas slow sequences required an adjustment in the upper (right-hand) region.

[17]The melody used by Kuwano *et al.* contained both long and short tones. Presumably, they were referring in their analysis to the length of the first tone in short–long and long–short sequences.

[18]This fingering would not be used for an extended chromatic scale, but it is quite natural for a five-note chromatic scale, though many alternative fingerings are possible.

[19]This interpretation is very tentative, as there seems to be a step size effect for the left hand in the low register which is just as large as that for the right hand in the high register. However, neither the step size main effect nor the register by step size interaction was significant for the left hand.

[20]It would be interesting to observe the same pianists' KOTs in more natural playing, without explicit instructions to play *legato*. In fact, at the end of the experimental session four of the present subjects played a simple monophonic tune three times with their right hand in the middle register, to provide performance data for a different study. Three of them produced KOTs that were 40–50 ms shorter than in the most comparable experimental condition, but the fourth pianist produced times that were about 15 ms longer, on the average. Their "overlap profiles" for the tune were quite dissimilar, possibly due to different choices of fingering. Clearly, there is much more to be learned about the factors that cause systematic variation in KOTs.

[21]The average MIDI velocity in the pianists' playing was a good deal higher than the fixed velocity in the perception experiment, but this was partially offset by a relatively lower volume of the auditory feedback. As mentioned in an earlier footnote, however, the postrelease decay characteristics of the digital piano tones did not vary much with dynamic level.

[22]It could be argued that the experiment should have been designed to separate these two factors from the outset. However, this is impossible without a radical change in fingering patterns and scale construction, which would raise new problems. For example, a pitch interval larger but more dissonant than the minor third (3 st) is the tritone (6 st), but it would permit only a three-tone *arpeggio* with the fingering 1-3-5-3-1. Passing the thumb under the other fingers is undesirable in a study of *legato*, as it almost certainly reduces KOT.

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