TECHNICAL NOTES AND RESEARCH BRIEFS

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Objective performance analysis as a tool for the musical detective [43.75.St]

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The expression and individual character of a musical performance resides in its microstructure. which includes variation in the exact timing and intensities of the tones played. Each performance has a unique microstructure which cannot be reproduced exactly by a human performer. even though repeated performances by the same artist are often highly similar. Objective performance analysis (Seashore, 1936) thus makes it possible to distinguish an identical copy from a repeat performance with a high degree of confidence.

A demonstration of this capability was provided by an unexpected discovery during the analysis of 28 different recorded performances of Robert Schumann's famous piano piece, "Träumerei" (Repp, 1992). The measurements revealed beyond any reasonable doubt that one recording of older vintage, by the German pianist Elly Ney (Electrola WDLP 561), contained two identical sections four measures long.

The first eight measures of "Träumerei" are followed by a repeat sign in the score, which is obeyed in nearly all performances. When the expressive microstructures of the first and second renditions are measured and compared. they are usually found to be quite similar in any given performance. but never identical. Since artists are not machines. there is always a certain amount of uncontrolled variation in timing and intensity, in addition to any variation introduced deliberately by the artist. Such variation was also observed between the two renditions of the first four measures in Elly Ney's recording. The two renditions of measures 5–8, however, were virtually identical, within the limits of measurement error.

The evidence is presented in Fig. 1. Figure 1(a) shows the differences between the first and second renditions in the inter-onset intervals (IOIs) between successive (clusters of) tones, as measured in the digitized acoustic waveform (see Repp, 1992). Most of the intervals correspond to eighth-notes in the score; any longer IOIs were scaled down to the same level (e.g., the duration of a quarter-note IOI was divided by two). The vertical line divides measures 1–4 from measures 5–8. It is evident that the differences were much smaller in measures 5–8 than in measures 1–4. This was confirmed statistically by a one-way analysis of variance on the absolute difference values [$F(1,50) = 23.41, p < 0.0001$].

Three additional considerations suggested that the two renditions of measures 5–8 were in fact identical. First. the differences observed in that section of the music were within the range of measurement error estimated by Repp (1992). The two 25-ms discrepancies in measure 8 occur in adjacent positions and are of opposite sign. which suggests a single larger measurement error in locating a tone onset. This was confirmed by re-examination of the waveforms. Second. the average difference in measures 1–4 was − 18.38 ms (s.d. = 31.65 ms), which indicates a slower tempo in the second than in the first rendition. whereas the average difference in measures 5–8 was 1 ms (s.d. = 8.36 ms), suggesting identical tempi. The third and most important argument is that, whereas the differences found in measures 1–4 are quite typical of those found between two renditions of the same music by the same artist (cf. Repp, 1990, 1992), agreement as high as that observed in measures 5–8 has never been encountered by this author. The highest correlation between the IOIs in the two renditions of measures 1–8 for any individual artist was 0.95 (Repp, 1992); for Elly Ney, the correlation was 0.92 for measures 1–4 but 0.998 for measures 5–8.

These arguments are further corroborated by intensity measurements. The particular measure employed here was the rms sound level of the fundamental frequency ($F0$) in the spectra of successive melody tones. determined by a FFT over a 51.2-ms window whose left edge coincided with tone (cluster) onset. as determined in the waveform (cf. Repp, 1993). Figure 1(b) shows the differences between the first and second renditions in this measure. Again. the absolute differences in the second half are much smaller than those in the first half [$F(1,48) = 16.76. p < 0.0003$].

Although the sound spectra were determined automatically and thus error-free. errors in locating tone onsets. random surface noise from the record. and rounding to the nearest dB value caused measurement error in sound levels. Note that the largest discrepancy. in measure 3. coincides with the single large timing measurement error [Fig. 1(a)]. The other discrepancies. too, seem within plausible error margins. The average difference in measures 1–4 was 2.04 dB (s.d. = 3.56 dB), which suggests a somewhat

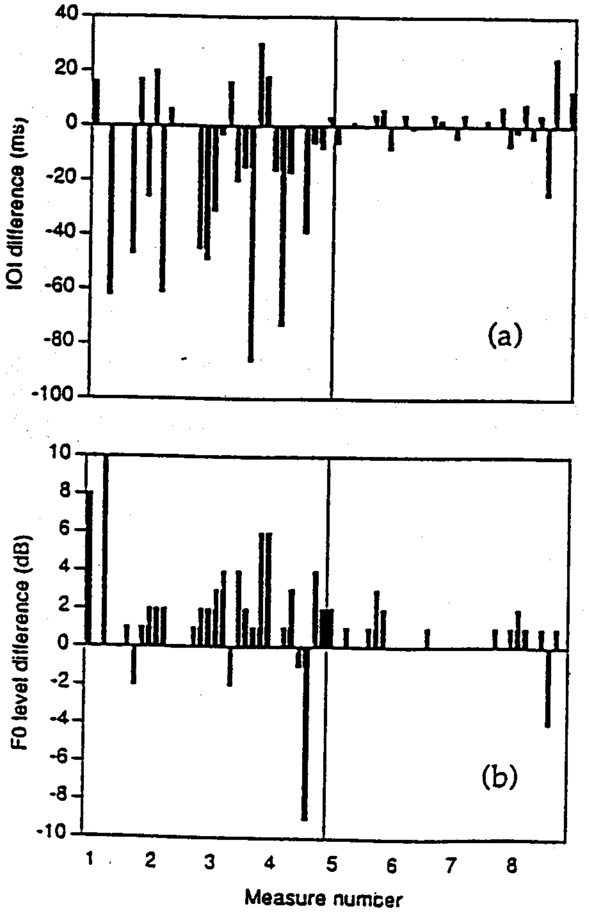

FIG. 1. Differences between the first and second renditions in (a) inter-onset intervals (IOIs) and (b) sound levels of the fundamental frequencies ($F0$) of the melody tones in the spectrum.

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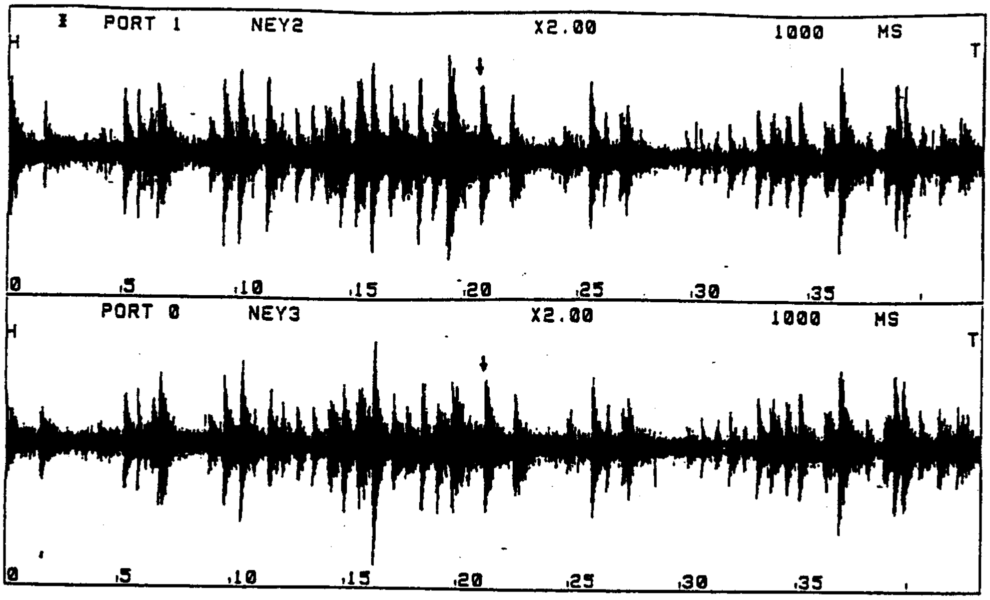

FIG. 2. Acoustic waveforms of the two renditions of measures 1–8 (NEY2 and NEY3, respectively, in this display). The time scale is in seconds. The arrows mark the beginning of measure 5. (The waveforms for measures 5–8 are slightly misaligned due to measures 1–4 being slightly longer overall in the second than in the first rendition.)

higher dynamic level in the second than in the first rendition, whereas the average difference in measures 5–8 was only 0.5 dB (s.d. = 1.24 dB), suggesting a slightly elevated level. There are not sufficient data available on intensity measurements to judge whether such close agreement as observed here in measures 5–8 could ever be achieved by an artist playing the same music twice; however, it seems highly unlikely.

The essentially independent statistical comparisons of timing and intensity patterns lead to the inescapable conclusion that the second rendition of measures 5–8 is not only much more similar to the first rendition than is the case for measures 1–4, but more similar than is humanly possible. This indicates that measures 5–8 were in fact duplicated by the recording engineers. This was presumably done to cover up some technical problem at the time when the original 78-rpm recordings (dating from the late 1930s) were transferred to LP format. This may be the first time that objective performance analysis has uncovered such "surgery" in a commercial recording.

Of course, the same conclusion could have been reached by simply comparing the raw acoustic waveforms or their amplitude envelopes. The waveforms of the two renditions are shown in Fig. 2. Visual comparison fully confirms the conclusion that the first halves of the waveforms are different, whereas the second halves (starting at the arrows) are identical, except for occasional spikes and other small differences caused by pops and surface noise from the record. However, a comparison of waveforms may not be practical if the location and extent of a duplicated portion are unknown. Moreover, if copied music were processed in any way to conceal its identity (e.g., by changing its tempo, filtering the sound, or mixing it with another sound track), waveform comparisons would be much less informative, whereas analysis of musical microstructure, particulary of timing patterns, could still reveal identity (cf. Howard *et al.*, in press).

A much more difficult question than that of literal identity would be whether two different performances of the same music are by the same artist or by different artists. Analysis of musical microstructure can provide relevant information here, too, provided a database of many different performances of the same music is available. Repp (1992), for example, has observed that different performances by the same artist, recorded many years apart, still tend to be more similar to each other than to almost any other performance by a different artist. Clearly, however, there is a much higher margin of error here, which is inversely related to the size of the available database.

The most difficult question to pose to a musical detective would be whether two performances of *different* music are by the same artist or by two different artists. This situation is comparable to that encountered in forensic voice recognition, where the speech samples being compared usually differ in content. Although some individual artists are said to have a recognizable individual style that is revealed in all their performances, this is probably too subtle a characteristic to be demonstrated objectively at this stage of the game. Once extensive performance databases are available, however, the question could be addressed, especially since artists, unlike criminals, are not motivated to disguise their individual characteristics.

ACKNOWLEDGMENTS

This research was made possible by the generosity of Haskins Laboratories and by support from NIH Grant No. RR-05596 to Haskins Laboratories. I am grateful to the record library at Yale University (Karl Schrom, supervisor) for providing the Elly Ney recording, and to Allen Hirson (City University London) for drawing my attention to the potential forensic applications of objective music performance analysis.

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