C. RULES FOR AUTOMATIZED PERFORMANCE OF ENSEMBLE MUSIC*
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Abstract
Recently developed parts of a computer program are presented that contain a rule system which automatically converts music scores to musical performance, and which, in a sense, can be regarded as a model of a musically gifted player. The development of the rule system has followed the analysis-by-synthesis strategy; various rules have been formulated after having been suggested by a professional string quartet violinist and teacher of ensemble playing. The effects of various rules concerning synchronization and timing and, also, tuning in performance of ensemble music are evaluated by a listening panel of professional musicians. Further support for the notion of melodic charge, previously introduced and playing a prominent rule in the performance rules, is found in a correlation with fine tuning of intervals.

Introduction
It is a well-known fact that musicians do not replicate in detail the music score. The score merely serves as a nominal description of the music, requiring an interpretation and this interpretation is signaled to the listener in terms of significant deviations from the nominal score which consequently seem musically important and meaningful.

Here we will present some recent results from a project where an analysis-by-synthesis strategy is applied to music performance. Numerous reports have already been published on this project previously (e.g., Friberg & Sundberg, 1986; Friberg, Frydén, Bodin, & Sundberg, 1988; Sundberg & Frydén, 1985; Sundberg, Askenfelt, & Frydén, 1983a; Sundberg, Frydén, & Askenfelt, 1983b; Thompson, Friberg, Frydén, & Sundberg, 1986). The scenario is a music teacher, who’s skill is beyond any doubt, teaching the computer how to perform in a musically acceptable manner. Thus, a basic idea in this project is to make use of a musician’s intuition and musical ideas as revealed by himself by introspection and as developed over a long period of time by his experience of teaching.

The analysis-by-synthesis strategy for analyzing music performance complements the method of collecting measurements from actual performances, which has been applied in most investigations (see e.g., Bengtsson & Gabrielsson, 1977; Clarke, 1985; Edlund, 1985; Gabrielsson, 1987; Shaffer, 1981; Sloboda, 1983; Todd, 1985). The limitations and advantages of these two methods have been discussed extensively elsewhere (Thompson & al., 1986). Analysis-by-synthesis has been much less used (Clynes, 1983). There are certainly advantages and limitations associated with both these methods (Gabrielsson, 1985). An important advantage is that even such elements of music performance can be revealed and analyzed, that are used only occasionally, and are hence difficult to find by means of a statistical processing of measurement data. For instance, if there are many reasons to shorten a note, it is a sizeable task to identify the various reasons by measuring on performances. It is also interesting that in performance research based on measurements, much more attention has been paid to regularly recurring events, such as the duration pattern during a bar, while expressive effects not affiliated with the bar unit have been largely neglected. In any event, there seem to be certain important and unique advantages associated with the analysis-by-synthesis strategy as applied to music performance, and we found it worthwhile to exploit these advantages.

In previous experiments, we have dealt with the performance of one part melodies and excerpts. Several rules have been formulated and tested. When one or several rules have been applied, musically experienced judges find that the musical quality of the performance increases (Thompson & all, 1986).

Undoubtedly, these rules must apply also to polyphonic music in one way or the other. In the following, we will mention first some rules that seemed to be of particular relevance in an attempt to synthesize performance also of polyphonic music. Then, two basic aspects of ensemble playing will be considered that seemed to ask for priority in synthesis of ensemble performance:

1. How is temporal coordination achieved?
2. What principles are used for tuning chords?

Most of the background of the first question has been described above already; the deviations from the nominal durations of the notes seem essential in music performance but will differ between different voices in a piece of music. Thus, whose time table is accepted by the others, and at which places in the piece do all musicians synchronize their tone onsets perfectly?

The background of the second question deserves more detailed comments. Tuning has been a classical concern in music theory. Reviews of measurements of tuning in performance have been offered by Ward (1970) and by Sundberg (1982), and, more recently, experimental work has been
reported on perceptual aspects of tuning (Hall & Hess, 1984; Rasch, 1985; Vos, 1986). Theoretically, several tuning recipes compete. One candidate is the just tuning. It implies that all chords are played beat-free, which is often considered to be an advantage. This means that the fundamental frequencies in all simultaneously sounding major triads be tuned to the frequency ratio 4:5:6, if instruments generating tones with harmonic spectra are used. Another alternative is the equally tempered tuning. In it, the octave is split into twelve equally wide intervals all having the frequency ratio 1:21/12.

Just tuning is sometimes referred to as pure. However, in the present article, the term pure will be used for "sounding appropriately tuned" or "perfectly in tune". Obviously, this is sometimes quite different from being in accordance with just tuning.

Fig. 1 summarizes measurements made on various types of musical performance. The interval sizes have been normalized, such that the data show the deviations in cents from what the interval is in the equally tempered scale. It can be seen that just tuning is far from universally applied in music performance. Rather, the intervals are played wider than just, except for the minor second which is played considerably narrower than just.

In ensemble music performance, most musicians are free to decide themselves the exact fundamental frequency of the tones they are playing. This allows context-dependent intonation. Thus, they can adjust the frequency of each note such that each chord receives its optimal tuning or such that each melodic interval is optimally sized. According to the general opinion among musicians, this context-dependent tuning of
each note is a must in ensemble performances. For instance, all professional players of bowed instruments would agree that they have to move their tuning finger if a note is changed from F sharp to G flat, and Shackford (1961; 1962a; 1962b) found these two intervals to be clearly differentiated in string music performance.

In his survey of data on tuning performance, Ward (1970) found that most intervals except the minor second are played wider than in the equally tempered scale. However, this does not appear to be the whole truth. In an investigation of chord intonation in barbershop singing, several intervals were found that were narrower than in the equally tempered scale (Hagerman & Sundberg, 1982). Also, within a single note, the fundamental frequency is sometimes observed to change, apparently from one value to another (Sundberg, 1982). This suggests that the fundamental frequency averaged over an entire note may be misleading.

It turns out that beat-free chords cannot be combined with a tuning that is perceived as melodically appropriate. Tuning the minor second narrow, leads to a conflict with the demands of just tuning. Let us take the progression dominant - tonic, as an example. Melodically, it normally contains a minor second from the third of the dominant to the root of the tonic. Using instruments with harmonic spectra, a beat free third implies the fundamental frequency ratio of 4:5. This third is 16 cents flatter than the corresponding value in the equally tempered scale. Consequently, if the third of the dominant chord is tuned beat-free, the minor semitone step up to the root of the tonic will be 16 cent wider than in the equally tempered tuning. Thus, there is a conflict between what is perceived as optimal harmonically and melodically. Therefore, a third alternative tuning must be postulated. Henceforth, though as yet poorly defined, the tuning that yields intervals sounding melodically pure will be referred to as melodical tuning.

In any event, it can be assumed that the equally tempered scale, though used in some keyboard instruments, cannot a priori be regarded as the only possible solution to the tuning problem in ensemble performance. On the contrary, the details of the musicians' tuning strategies must be said to be largely unknown. Therefore, a primary task was to look for better tuning and intonation alternatives.

Procedure

Fig. 2 gives an overview of the strategy. The input is the musical score, which, voice by voice, is written into a Macintosh microcomputer. This input can be complemented by various interpretational details, such as phrase and subphrase boundaries, harmonies, ties, etc. Then, the input is processed by the RULLE program, which automatically computes the performance and converts it into control signals for a synthesizer, using the MIDI standard. The synthesizer used is mostly a specially
constructed machine, SISYPHOS, a sampler-type machine that reads previously stored wave forms at a speed determined by the fundamental frequency. One advantage with this device is that fundamental frequency can be controlled with an accuracy of +/- 0.85 cent.

\[ \text{Fig. 2. Block scheme showing the analysis-by-synthesis strategy used in the present project. The score is written into a Macintosh microcomputer in which the RULLE program converts it into control signals in a MIDI format to a synthesizer.} \]

Into the RULLE program, written in the Le Lisp computer language, context-dependent performance rules are introduced (Friberg & Sundberg, 1986). These rules shorten and lengthen the durations of single notes, increase or decrease their sound level, perform fine tuning of pitch, generate crescendos and decrescendos, distribute markers at phrase and subphrase endings as defined in the input notation. The program allows the testing of the musical effects of each single rule on the performance. In this way, the effect on performance of every single rule can be tested, demonstrated, and assessed.

In most cases, the effects of the rules are quite clearly demonstrated by this experimental setup, and only exceptionally there has been any disagreement between the authors as to whether or not a rule improved a performance. Still, in order to evaluate the various rules formally, we have had a panel of 2 professional violin players and 8 advanced music conservatory students to assess the effects. In this
experiment, the subjects listened to different computer generated renderings. Their task was to rate the musical quality of the performance in a number between 0 and 7, 0 being poorest and 7 being the best.

Results

A. Monophonic Rules
Melodic charge

Musical notes do not form a society of equality. On the contrary, some notes are important, i.e., unexpected, while others are less important, i.e., predictable. It seems necessary to take this into account during playing. Assume, for example, that the note of C sharp occurs in a C major tonality which is a remarkable event in traditional harmony. If the player does not mark this prominent note when playing, it sounds musically insensitive. We have arrived at the following method for marking a note's prominence.

Each note is assigned a value reflecting its melodic charge. The basis of this concept is borrowed from the circle of fifths, as illustrated in Fig. 3: a note's melodic charge reflects its distance along the circle of fifths from the root of the prevailing chord. Note, however, that the distribution of melodic charge is unsymmetrical around the circle; the numbers on the subdominant (left) side of the circle are negative and greater as compared to the numbers on the opposite side, which are positive. For example, three fifth steps down from the root correspond to a melodic charge of -4.5, while three fifth steps up correspond to the charge value of 3.0. In previous reports on this project, the absolute value, only, of the melodic charge has been used. Unless otherwise stated, the term melodic charge will henceforth be used for the absolute value of the melodic charge, as before.

Fig. 3. Definition of melodic charge of the scale tones in tonal music by means of the circle of fifths. Note that the values are asymmetrically distributed around the reference which is the root of the prevailing chord, and that the charge is negative in the left, subdominant, half of the circle.
While the concept of melodic charge may seem farfetched, the usefulness of the circle of fifths to describe in a compact form musically relevant aspects of tones in traditional tonal music is well-known. As shown in Fig. 4, melodic charge shows a significant correlation with the mean probe tone ratings for the tones in the major scale, that Krumhansl & Kessler (1982) reported from an experiment where listeners rated how well different tones served as a continuation of a reference scale (Sundberg & Frydén, 1987). Also, as shown in the same figure, melodic charge clearly correlates with the frequency of occurrence of the various scale tones in Schubert themes, as reported by Knopoff & Hutchinson (1983). This suggests an interpretation of melodic charge: assuming that rarely occurring notes are remarkable, a note's melodic charge may reflect its remarkable.

According to our rules, melodic charge is signaled in three different ways in a performance: (1) by a lengthening of the note's duration by an amount equal to 2/3 of the melodic charge, in msec; (2) by an increase of the note's sound level by an amount of dB equal to 0.2 times the melodic charge; and (3) by an increase of the note's vibrato extent by an amount of 0.03 times the melodic charge, in percent. The effect is illustrated in Fig. 5.

Harmonic charge

The principle of inequality seems to apply also to chords. For instance, a G major chord appearing in a C major tonality is not very remarkable, while an A major chord occurring in the same tonality is much more remarkable. Again, it sounds musically insensitive if a player overlooks this when playing.

We have derived a quantitative measure of this remarkable of chords from the chord notes' melodic charges, and we have called the resulting entity harmonic charge. The harmonic charge of a chord is a weighted sum of the chord notes' melodic charges as defined using the root of the tonic as the reference: for a triad it equals the melodic charge of the root plus 2/3 of the melodic charge of the third plus 1/3 of the melodic charge of the fifth. The values thus obtained are then normalized such that the harmonic charge of the tonic becomes zero. Fig. 6 shows the harmonic charge values for some chords.

Harmonic charge may seem as farfetched as melodic charge. However, also in this case listeners' experiences can serve as a support. Krumhansl & Kessler (1983) also presented to listeners different probe chords following a reference cadence that defined the tonality and asked the subjects to rate how well the probe chords fitted as a continuation of the reference cadence. The probe chord ratings showed a significant correlation with harmonic charge, as shown in Fig. 7.

According to our rules, the harmonic charge is reflected in the performance in terms of crescendos and decrescendos, as well as in
Fig. 4. Correlation of melodic charge with (left) the probe tone ratings for the tones in the major scale, according to Krumhansl & Kessler (1982) and (right) with the frequency of occurrence of the various scale tones in Schubert themes, as reported by Knopoff & Hutchinson (1983).

Fig. 5. The effect of melodic charge on the performance, according to the rule system: (1) a lengthening of the note's duration; (2) an increase of the note's sound level; and (3) an increase of the note's vibrato extent.
Fig. 6. Harmonic charge values for some chords symbolized by their harmonic function in tonal music: T=Tonic, S=subdominant, D=Dominant, R=Relative. In a C-major context, the chords are the following: SS=B flat major, S=F major, T=C major, D=G major, DD=D major, SR=D minor, DSR=A major, TR=A minor, DTR=E major, DR=E minor.

Fig. 7. Harmonic charge versus the probe chord ratings reported by Krumhansl & Kessler (1983).
minute accelerandos and rallentandos and tenutos, as illustrated in Fig. 8. The sound level increases toward increases in harmonic charge and vice versa; the amplitude of the first note after each chord change is increased by a number of dB equal to a constant times the harmonic charge value of the new chord, and the intermediate notes are given intermediate amplitudes. In this way, crescendos and decrescendos are created. Too slow crescendos are hard to detect and are avoided by delaying crescendo starts until 1.9 sec ahead of the chord change, whenever needed. Unlike crescendos, dEcrescendos start immediately after the chord change.

![Graph](image)

Fig. 8. The effect of harmonic charge on the performance, according to the rule system: (1) crescendos and diminuendos; (2) concomitant tempo changes; and (3) small tenutos.

Apart from these long-term sound level variations, the harmonic charge also generates expressive variation of the notes’ durations. In a crescendo, the durations of the notes are lengthened by a factor proportional to the increase in sound level, as illustrated in Fig. 8. Also, a small tenuto is added to the first note over a new, harmonically charged note.

B. Polyphonic rules

Synchronization

Above, two performance rules out of a total of about 20 have been presented. As mentioned, the musical effects on performances from these rules have been approved by panels of musically experienced listeners. Therefore, it seems reasonable to assume that these rules are valid also in ensemble playing. If so, each member of an ensemble will arrive at a time pattern that is suited for his own voice only. In this way, a number of competing time tables would result in an ensemble, so some decision must be taken as to which one is going to rule over the others.

One way of maintaining synchronization is obviously that each
musician sticks to the nominal durations. There are strong indications that this is not the normal solution in ensemble performance. We may merely point to well-known phenomena such as final ritard, tenuto and other means of expression which are undoubtedly used also in ensemble performance. We tried two alternative ways of achieving synchronization between voices.

One possibility is that all musicians make all perturbations of the nominal durations that are required but scale them such that the entire ensemble is synchronized once per bar, e.g., on the main beat. This once-per-bar principle would maintain a coordination and yet offer some leeway for individualization of the various parts. It was selected as one of the two alternatives in the listening test.

Another possibility is that everything that is vertically aligned in the score is perfectly aligned also in time and that the player, who is playing the shortest or melodically most charged note, dictates the time table for the remainder of the ensemble. Note that this principle does not require everything to be played as nominally written in the score. This synchronization on the shortest notes was selected as the second alternative in the listening experiment.

![Musical notation](image)

Fig. 9. The excerpt from String quartet no 5, C major, second movement by Franz Berwald used in the synchronization test. The circled notes show the synchronization voice, obtained by selecting, at each moment, that voice which plays the shortest and melodically most charged notes.
We used the following strategy in order to automatically derive such a performance from the score. First, all voices were processed by all rules affecting amplitude or vibrato. Secondly, a new voice was derived from the score. This voice was built up by the shortest note that appeared in the score in each moment. In cases where there are more notes sharing the shortest note value, that note was selected which had the highest melodic charge. The "synchronization voice" thus obtained jumps boldly from one part to the other, as is illustrated in Fig. 9. Interestingly, it seems far from void of musical meaning. Once this synchronization voice has been constructed, it is processed by all performance rules that affect the duration of the notes, and all ensemble members play in synchrony with this voice.

Our panel of musicians rated the quality of three synthetic performances "with regard to ensemble playing, i.e., how simultaneously the musicians played". The excerpts are listed in Table I. Each was presented three times in random order on a test tape avoiding repetitions of the same excerpt in sequence. In the examples, the synchronization was made according to either of the two principles mentioned. The examples were presented over loudspeakers to all subjects at a comfortable listening level. The subjects gave their answers on standard sheets.

Table I. Results from the listening experiment in which professional musicians rated the quality of "togetherness" in synthesized performances of three excerpts, where the synchronization was made according to either the "once per bar" principle or the "shortest note" principle (see text).

<table>
<thead>
<tr>
<th>Synchronization Strategy</th>
<th>&quot;Once per bar&quot;</th>
<th>&quot;Shortest note&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>S D</td>
</tr>
<tr>
<td>EXCERPT</td>
<td>rating</td>
<td></td>
</tr>
<tr>
<td>H. L. Hassler: Madrigal &quot;Nun fanget an&quot; for 5 voices</td>
<td>5.18</td>
<td>1.05</td>
</tr>
<tr>
<td>F. Berwald: Bars 58 to 69 from String Quartet No 5, C major</td>
<td>2.20</td>
<td>1.19</td>
</tr>
<tr>
<td>J. S. Bach: Bars 17 to 33 from the Ricercar a 6 voci from Musikalisches Opfer, BWV</td>
<td>4.85</td>
<td>1.56</td>
</tr>
</tbody>
</table>
The results, also shown in Table I, showed no preference in the case of the Hassler example, where both principles happened to yield very similar results. Less for the Bach excerpt and, more for the rhythmically vivid Berwald excerpt, however, there was a clear preference for the principle to synchronize on the shortest notes. According to the analysis of variance, the subjects differed significantly in their answers (p<0.01) and, also, the excerpts significantly influenced the results. Still, averaging over all excerpts, the synchronization on the shortest notes gave significantly better ratings than the synchronization on the bar (p<0.01).

These results indicate a preference for the principle that all notes aligned in the score should be synchronized in the performance and that a possible timing strategy is that the player who plays the shortest and melodically most charged notes decides the time table for his fellow players. This suggests that, at any moment, every member of an ensemble has to listen carefully to what his fellow players are playing and join the timing produced by the most vivid musical motion, unless there is a conductor to take the responsibility for the synchronization.

Tuning

In the same listening session, different tunings were also evaluated by the panel of ten professional musicians. Two tunings tried were just tuning and equally tempered tuning. In addition, we also wanted to try melodical tuning. However, as available data on melodical tuning were incomplete, we first had to carry out a complementary tuning experiment.

In an experiment, we asked a very proficient violinist to adjust a complete set of intervals. The tones were produced by a synthesizer controlled from the Macintosh computer by a programmer who changed the tuning of the interval according to the desires of the musician. Repeated attempts to tune the same interval showed a surprisingly small variation. Often, our musician replicated his previous settings within 0 or 2 cents except for occasional values that deviated by 10 cents or more from the mean. This is an amazingly high reproducibility suggesting that his tuning faithfully reflected accurately fixed tuning ideals. His interval settings are presented in Fig. 10 together with those shown previously in Fig. 1.

There is a clear tendency to increase the contrast between flattened and sharpened notes, so that flattened notes are tuned flat and sharpened notes are tuned sharp, as compared with the equally tempered tuning. In traditional harmony, a flattened note is typically followed by a falling minor second (e.g., as in the sequence A flat --> G) while a sharpened note is typically followed by a rising minor second (e.g., as in the sequence G sharp --> A). Therefore, the tendency to increase
Fig. 10. Deviation from just from equally tempered tuning of melodic interval tunings as produced by a professional violin player. Hatched areas show the data scatter in the tunings of melodic intervals shown in Fig. 1.

Fig. 11. Deviation from just tuning (left) and from equally tempered tuning (right) of the melodic interval tunings shown in Fig. 10 plotted as function of signed melodic charge.
the contrast between flattened and sharpened notes can also be seen as a tendency to play the minor second narrow.

Interestingly, these interval tunings seem related to the signed melodic charge of the upper note of the interval. Fig. 11 shows the settings, expressed as deviations from just tuning (left) and from the equally tempered tuning (right). In both graphs, the settings are given as function of the signed melodic charge of the upper note of the interval, assuming the lower note of the interval as the reference. The pitch symbols refer to the names of the upper note of the interval, using C as the lower reference note. Intervals "aiming" upward, i.e., potentially followed by a rising major second, e.g., a D sharp, are symbolized by sharps, and intervals "aiming" downward in the same sense, e.g., an E flat, by flats.

When expressed as deviations from just tuning, an overall tendency can be observed for the intervals to be expanded with increasing signed melodic charge. However, the scatter is considerable, and the data points are clustered in groups.

If, instead, the data are expressed as deviations from the equally tempered scale, as in the right graph, an almost linear function is obtained. This result is interesting, as it suggests the possibility that the equally tempered scale may serve as a frame of reference for interval tuning in music performance practice. Thus, the equally tempered scale may not necessarily be only a mathematical construct, but may also represent a psychological reality.

The straight line approximation derived by linear regression analysis (r=0.924) yields almost just fifths, 701.4 cent wide on the dominant side of the circle of fifths, and slightly more on the subdominant side. These settings yielded a series of interval settings that we accepted as a fair approximation of melodic tuning.

Thus, in the listening test, the subjects listened to three excerpts played in three different tunings: (1) just tuning, (2) equal temperament, and (3) melodic tuning. In addition, we also tried (4) a combination of just and melodic tuning. The reason was that neither melodic, nor just tuning sounded throughout acceptable in all musical contexts. Rather both sounded badly out of tune, though in different places in the pieces. According to the fourth alternative, all notes were tuned in accordance with melodic tuning at the onset and, after 10 msec, the tuning changed to just during 70 msec, according to a cosine curve.

The excerpts are listed in Table II. They represented different uses of harmony. One consisted of the first 8 bars from Gesualdo's madrigal "Belt, poi che t'assenti". It contains frequent examples of chromatic changes of notes. Another example was a 15 bar long Fancy, F major, by Purcell. It contains many instances of melodic minor seconds. The third example was a choral written in four voices by the contempora-
ry Swedish composer Sven Erik Bäck ("Du som gick före oss, Thou, who went ahead of us").

Each excerpt was presented in each of the four tunings, and, as before, each example occurred three times in random order on a test tape that the subjects listened to over loudspeakers at a comfortable loudness level. The subjects' task was to rate the quality of the tuning, taking both harmony and melody into consideration, and they gave their ratings on a protocol sheet. The mean ratings are shown in the same Table II.

Table II. Average rating and change in rating of just, melodical, and just-to-melodical tunings, as compared with equally tempered tuning.

<table>
<thead>
<tr>
<th>Tuning</th>
<th>Example</th>
<th>Mean</th>
<th>SD</th>
<th>Change re Eq. Temp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>EQ. TEMP</td>
<td>Gesualdo</td>
<td>3.5</td>
<td>1.53</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Purcell</td>
<td>3.9</td>
<td>1.69</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bäck</td>
<td>4.75</td>
<td>1.14</td>
<td></td>
</tr>
<tr>
<td></td>
<td>All examples</td>
<td>4.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>JUST</td>
<td>Gesualdo</td>
<td>3.77</td>
<td>1.99</td>
<td>+0.27</td>
</tr>
<tr>
<td></td>
<td>Purcell</td>
<td>1.37</td>
<td>1.46</td>
<td>-2.53</td>
</tr>
<tr>
<td></td>
<td>Bäck</td>
<td>4.35</td>
<td>1.56</td>
<td>-0.40</td>
</tr>
<tr>
<td></td>
<td>All examples</td>
<td>3.16</td>
<td></td>
<td>-0.89</td>
</tr>
<tr>
<td>MELODICAL</td>
<td>Gesualdo</td>
<td>1.63</td>
<td>1.50</td>
<td>-1.87</td>
</tr>
<tr>
<td></td>
<td>Purcell</td>
<td>3.6</td>
<td>1.94</td>
<td>-0.3</td>
</tr>
<tr>
<td></td>
<td>Bäck</td>
<td>3.55</td>
<td>1.56</td>
<td>-1.2</td>
</tr>
<tr>
<td></td>
<td>All examples</td>
<td>2.93</td>
<td></td>
<td>-1.12</td>
</tr>
<tr>
<td>MEL-JUST</td>
<td>Gesualdo</td>
<td>3.27</td>
<td>1.51</td>
<td>-0.23</td>
</tr>
<tr>
<td></td>
<td>Purcell</td>
<td>2.28</td>
<td>1.22</td>
<td>-1.62</td>
</tr>
<tr>
<td></td>
<td>Bäck</td>
<td>4.35</td>
<td>1.52</td>
<td>-0.40</td>
</tr>
<tr>
<td></td>
<td>All examples</td>
<td>3.30</td>
<td></td>
<td>-0.75</td>
</tr>
</tbody>
</table>

According to an analysis of variance, all factors produced significant differences: subjects, excerpts, and tuning (p<0.01, in all these cases). A major reason for this significance was the fact that the subjects answered consistently when rating the three copies of each example. In comparing means for single examples, the confidence interval at the level p<0.05 was 0.57, i.e., differences greater than 0.57 are significant at this level. In comparing means over all three examples, the corresponding value is 0.32.

Much to our surprise, the panel seemed to prefer the equally tempered tuning to just melodical, as well as to just-to-melodical tuning.
However, this preference was dependent on the music, as mentioned.

For the Purcell example, containing several minor second intervals, melodical tuning was almost as highly rated as equally tempered tuning, while for the Gesualdo and Bäck examples, composed in a homophonic, chordal style, just tuning was almost as highly rated as equally tempered tuning. The melodic-to-just tuning was slightly better than the just for the Purcell example and slightly better than melodic for the Gesualdo and Bäck examples.

These results offer good reasons for rejecting the hypothesis that just intonation can be regarded as an optimal general solution in ensemble performance. Also, it can be concluded that in tuning, the musical context must be taken into account; chords apparently sound better in just tuning while minor second sound better in melodical. Our melodic-to-just did not represent an alternative superior to the equally tempered tuning but still improved results slightly both in cases when just and melodical sounded badly out of tune.

Discussion

The present investigation considered two aspects of ensemble performance: synchronization and tuning. As regards synchronization, the results suggest that musicians have to follow, at each moment, the timing of a crucial voice which is composed from excerpts from various voices. This seems convincing in the sense that most musicians would agree on the necessity of invariably listening to the fellow players. During rehearsals, an important goal may be to learn the other voices and their possible time tables.

This rule for the synchronization of ensemble playing may need to be complemented by other, style-dependent rules. For instance, in certain contexts one instrument may lead over the others, e.g., in order to avoid masking effects (Rasch, 1978; 1979; 1981). In jazz music, certain dialects seem to exist where one voice may lead or lag as compared with a stable reference beat. In general, the existence of a rule seems to add one more possibility of musical expression in terms of violating this law.

Regarding tuning, the results show that the equally tempered tuning is better than both just and melodic tuning, if applied throughout a piece. The reason may be simple brainwashing; we always meet this tuning in pianos, organs, and synthesizers. It may even be that the fact that we used a synthesizer, increased the jury's prejudices in this respect. An interesting future experiment would be to repeat our listening test using violin sound as offered by a modern high-fidelity sampler synthesizer.

The melodic-to-just tuning was not appreciated as highly as we had hoped. There may be several reasons for this. One is that the timbre
used in our experiment was strongly periodic and had prominent high partials that exposed tuning deficiencies in terms of salient beats. One problem was that the pitch transition were too apparent. It is possible that some musicians use vibrato to conceal tuning adjustments during playing. Also, if melodic-to-just tuning is applied in music practice, it would constitute a source of error in fundamental frequency measurements; it is not completely evident how a time average should be computed.

However, a string player is free to make a context-dependent choice of fundamental frequency. Therefore, it is not correct to infer that the equally tempered tuning is better than the other tunings also when the players are free to vary intonation. On the contrary, it seems likely that tuning is context-dependent, such that both the harmonic and the melodic functions of each note are taken into consideration. For instance, the musician playing the melody part in a homophonic written piece might play according to melodic intonation, while the accompanying instruments, providing the underlying harmonies, play in just tuning. In a predominantly polyphonic piece, on the other hand, the melodically most charged note may be played according to melodic tuning. The assumption that interval sizes are context dependent is also supported by the fact that some subjects found it difficult to give an overall rating, as they found both merits and deficiencies in most examples. In a future analysis of the context dependence of tuning, analysis-by-synthesis would offer an efficient tool.

The experiment where a musician tuned various intervals, one may argue, used a stereotype context, viz., the interval between the note and the note preceding it. Therefore, it is not clear where these tuning data can be expected to appear in music performance, where also other contextual factors are relevant, such as the note's position in the scale. In the setting experiment, the major and minor intervals were tuned with an imagined context, viz., that they were followed by a rising or falling minor second. Still, a more detailed analysis of the relevance of the context to tuning would be needed. It may be advantageous to let the subject use his own instrument in such experiments.

Nevertheless, the settings for the melodic tuning seem convincing. First, there was a fair agreement between these data and averages found in actual performances. Second, the subject was mostly able to replicate his settings with an amazingly high accuracy, which actually was slightly better than the best values found by Corso (1954) for unison settings. Third, his settings fitted nicely into the framework of the signed melodic charge.

The last mentioned fact is quite interesting. What does this correlation between tuning and the signed melodic charge suggest? According to previous research, a performance gains in musical quality if melodic charge is marked. One may speculate that also sharpening and
flattening of intervals is used as an *expressive means* in order to mark the melodic charge of the notes. This speculation is supported by an investigation by Makeig & Balzano (1962) showing that differently sized octave intervals had different expressive meanings.

The fact that the musician subject's tunings of the intervals clearly correlated with the melodic charge of the upper note is interesting also from another point of view. Melodic charge is derived from the circle of fifths. In fact, the same correlation coefficient was obtained if the position on the circle of fifths was used rather than the melodic charge in Fig. 11. This means that melodic tuning is very similar to the so-called Pythagorean tuning, in which all fifths are tuned just, or to 702 cent. In our musician subject's tuning, the mean fifth was 701.4 cent. This minute difference may seem small but gains in importance, the greater the number of fifths there is in an interval. Also, it should be kept in mind that the data showed important deviations from a straight line in this plot.

Finally, the use of rules for describing musical performance should be commented on. Before discussing this problem it is necessary to distinguish between two aspects of a rule. One is the class of notes that are being modified by the rules, i.e., the *target notes* of the rule. The other is the amount of modification that the rule generates in the target note's sound variables. This aspect will be referred to as the *rule quantity*.

Music is a form of communication by means of acoustic signals, obviously, implying that there are some conventions shared by the player and the listeners. The rules offer efficient tools for describing such conventions. On the other hand, a given piece of music can be performed in a number of different ways, while the use of rules seemingly implies that there is only one single performance possible.

One way of having the same rule system produce different performances is to allow variation of rule quantity. Many experiences support the assumption that this occurs in reality. We have noted several times that introducing a new rule into the system necessitated a reduction of quantities of one or more of the existing rules. We have also noted that comparatively acceptable performances could be generated with only a small number of rules, suggesting that some rules are not compulsory; the quantity of these *optional rules* may then be regarded as reduced to zero.

There may also be alternative rules. For instance, emphasis is expressed in several different ways in our system: sound level, duration, and vibrato amplitude. A rule may merely be a line in the musician's and the listener's internal dictionary which translates items of musical expression, such as emphasis, phase ending etc., into sound events, such as change in sound level, lengthening etc. This dictionary probably contains synonyms, and in selecting which synonym to use, the
musician would take into account the style of the piece, among other things. On the other hand, all rules would not be style-dependent. In a recent experiment, it was found that rules developed for traditional tonal music clearly improved the performance also when applied to contemporary music (Friberg & al., 1988).

Conclusions

Using the analysis-by-synthesis strategy allows comparative conclusions, only, i.e., it demonstrates which one of two or more alternatives is better while no conclusion can be drawn as to what is the best alternative. Given this limitation, the following conclusions can be inferred.

Temporal coordination in ensemble performance is achieved when all notes which are synchronized in the score are synchronized also in the performance.

Both harmonic and melodic factors influence the ideal tuning in ensemble performance.

If applied throughout a piece, the equally tempered tuning is better than both just tuning and melodic tuning.

The equally tempered tuning seems to serve as a baseline in tuning practise.

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References


