ISSN: 1938-2065

About Time: Strategies of Performance Revealed in Graphs

By

Elaine Chew
Queen Mary, University of London

Abstract

This paper describes how insights into performance strategies can arise from observations derived from measurements as well as visual inspection of graphs of expressive parameters. The widespread availability of tools for quantifying expressive parameters have made it possible to incorporate engineering approaches to the study of performance for both experts and novices. Scientific graphs map the evolution of these parameters over time, allowing investigations that reveal correspondence or a lack thereof between expressive gestures and musical structures. Three examples illustrate discoveries of principles of performance using a scientific approach. The first example compares three performances of Beethoven's Piano Sonata No. 14 in C# Minor, Op. 27, No. 2*, commonly known as the* Moonlight Sonata*, highlighting Schnabel's strategies for projecting long lines. The latter two examples are projects by engineering students with different degrees of musical training comparing guitar vs. piano performances of Granados'* Danza Española No. 5 *and tracing the evolution of vibrato over a century in a small sample of notes from Bach's* Violin Sonata No. 1*, respectively. These methodologies have the potential for transforming how musicians study and teach performance.*

Chew, E. (2012). About time: Strategies of performance revealed in graphs. *Visions of Research in Music Education, 20*. Retrieved from http://www-usr.rider.edu/vrme~/

“A hearing is a performance, a performance is a hearing.” – Jeanne Bamberger (2010)

Performers manipulate musical parameters such as tempo, loudness, articulation, pitch, and timbre to focus attention, to facilitate parsing of music material, and to create emotional affect. While the music score sometimes minimally prescribes when and how to vary these parameters, there remains a great deal of difference between notation and performance practice. The finer details of how these parameters are varied over time, and the generative principles underlying these actions, have eluded formalization. Until recently, there were no means by which to consistently describe these expressive choices and their realization.

Music psychologists have conducted much research on performance (Palmer, 1997; Gabrielsson, 1999). In recent years, the development of engineering tools for extracting, quantifying, and processing musical features such as tempo and loudness (Dixon, 2001; Dixon, Goebl, & Widmer, 2002) have enabled scientific approaches to expressive performance studies. The results of such analysis can give insights into fundamental musical concepts such as phrase groupings (Chuan & Chew, 2007; Cheng & Chew, 2008). Today, these tools and methodologies have reached a stage of development where they are now widely available and accessible to music scholars with implications for the teaching and study of music performance.

This paper provides three examples of how these tools for quantifying expression can be instruments for fruitful investigation that help explain the how and why of musical expression. These examples arose from a class the author taught on Musical Prosody and Interpretation in Spring 2010. After providing background on the class, the focus of this paper will shift to the three examples. The first example is built on Jeanne Bamberger's (2010) musical examples and observations in the guest lecture she gave to the class, and the latter two examples are student projects from the class.

Topics in Engineering Approaches to Music Cognition

The basis for this paper draws on material from or inspired by a course on Topics in Engineering Approaches to Music Cognition at the University of Southern California Viterbi School of Engineering. The course aims to impart knowledge on research directions in the chosen topic at the intersection of music and engineering to the extent that students can pose questions relevant to the field then seek and implement appropriate solutions to those questions.

The course design espouses both a constructivist and constructionist approach to learning at the intersection of music and engineering (Chew, 2006). The students' backgrounds range from fields in engineering to psychology to music composition and performance. Some have no formal instruction in music, and some are pursuing advanced degrees in music; the majority are graduate students in engineering. The students review recent publications on the topic, through which they learn by example, and design and implement a final project in the realm of the topic, through which they learn by doing. Students post all course material, better paper reports, and final projects online as open courseware (Chew, 2010, January).

The focus of this paper is material from the 2010 class, for which the topic was Musical Prosody and Interpretation. The course explored the role of musical prosody in conveying diverse interpretations in music performance, covering techniques for quantifying prosodic cues such as timing and loudness in music, the resulting accents and phrases, and how they map to perceived prominence and grouping. In addition to reviewing contemporary literature and the final class project, the teacher also assigned students practical homework to help them internalize the ideas covered in the material. The week-by-week details are reproduced in Appendix A, and a list and short descriptions of the students' projects are presented in Appendix B.

Figure 1. First fifteen bars of the Adagio sostenuto from Beethoven's *Moonlight Sonata* with triplet eighth note counts shown at the beginning of each bar.

Beethoven's *Moonlight Sonata* Performed by Barenboim, Pollini, and Schnabel

This section uses Jeanne Bamberger's example in the invited lecture she gave to the class on March 25, 2010 as a springboard to a discussion on how engineering tools and scientific methods can lead to discoveries about and validations of musical principles. In Bamberger's talk, titled "What is Time – a hearing is a performance, a performance is a hearing," she compared three performances of the first movement, Adagio sostenuto, of Beethoven's *Moonlight Sonata*, as well as three performances of the *Gigue* from Bach's *Cello Suite No. 2* (Bamberger, 2010). This section will focus on the first 15 bars of the Beethoven example (see Figure 1). The three performances of *Moonlight Sonata* that Bamberger discussed were by Daniel Barenboim (Beethoven, 1987), Maurizio Pollini (Beethoven, 1992), and Artur Schnabel (Beethoven, 2009).

In her presentation, Bamberger (2010) made two observations about Schnabel's playing, which are paraphrased as follows: (1) the left hand melodic line is prominent and outlines a long phrase that moves toward the beginning of the fifth bar; and (2) Schnabel does not dwell on the right hand melody's signature dotted rhythm motif, it is rather part of the flow of the music. These observations correspond to features in the tempo graphs obtained from the recorded performances.

Collecting and Processing of Tempo Data

The author manually annotated the onset of every triplet eighth note using Sonic Visualiser (Cannam, Landone, & Sandler, 2010), freely downloadable software developed at Queen Mary University of London for musicological studies (see Figure 2). The annotations were double checked both visually and aurally in the software. The time instants were exported as a time series to Matlab for computing and visualizing tempi.

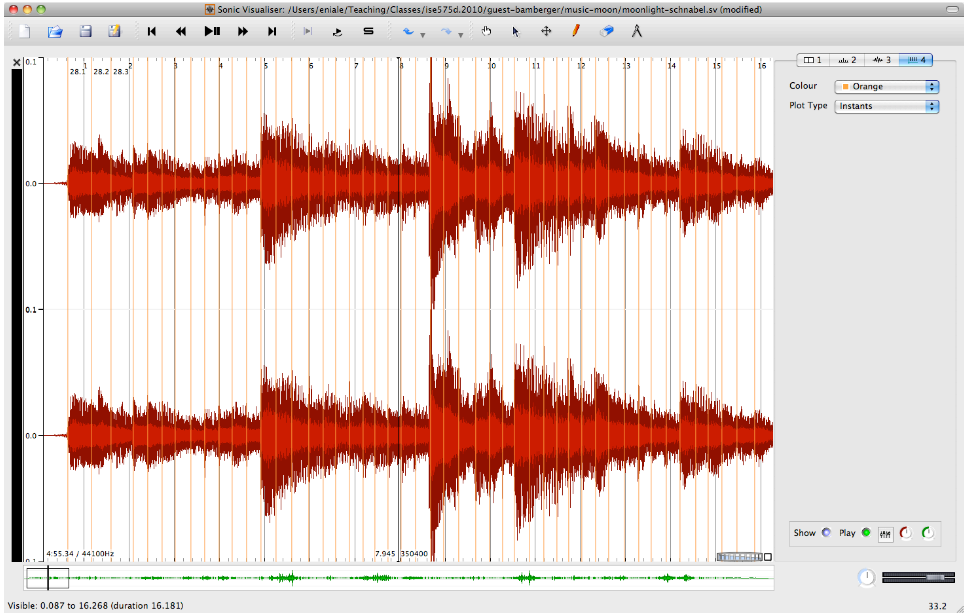


Figure 2. Annotation of eighth notes in Schnabel's performance of *Moonlight Sonata*.

A certain amount of data smoothing is necessary to make the graphs more readable by the human eye. Smoothing over too large a window can obscure important details in the performance, and too little smoothing can make the data hard to read. A minimal amount of smoothing was done: the local tempo at the onset time of any triplet eighth note was computed as the average tempo between the previous eighth note and the next eighth note (i.e., averaged over three eighth note onsets). More formally, if o_i is the onset time of the i-th triplet eighth note (in seconds), then the tempo (in beats per minute) at that time is given by:

$$b_i = \left(\frac{1}{o_{i+1} - o_{i-1}} \right) \times 60 \times 2/3 = \frac{40}{o_{i+1} - o_{i-1}}.$$

Figure 3 shows a graph of the tempo time series for the first fifteen bars of Beethoven's *Moonlight Sonata* performed by Barenboim, Pollini, and Schnabel, indexed (on the x-axis) by the triplet eighth note count. The corresponding musical passage and eighth note counts are shown in Figure 1. The vertical grid lines in Figure 3 mark the first note (beginning) of each bar, serving as indicators of downbeats and their immediately preceding bar lines.

The general tempo trajectory of a phrase is an ascending (due to acceleration into the phrase) then descending (deceleration toward the end of a phrase) arc. Such phrasing can occur at more than one level; external to the phrase grouping, agogic accents generate dips in the tempo curve; together with noise (random imprecision), these factors can make phrases less obvious in the graph. Nevertheless, it is possible to make out the general shape of each phrase by inspection.

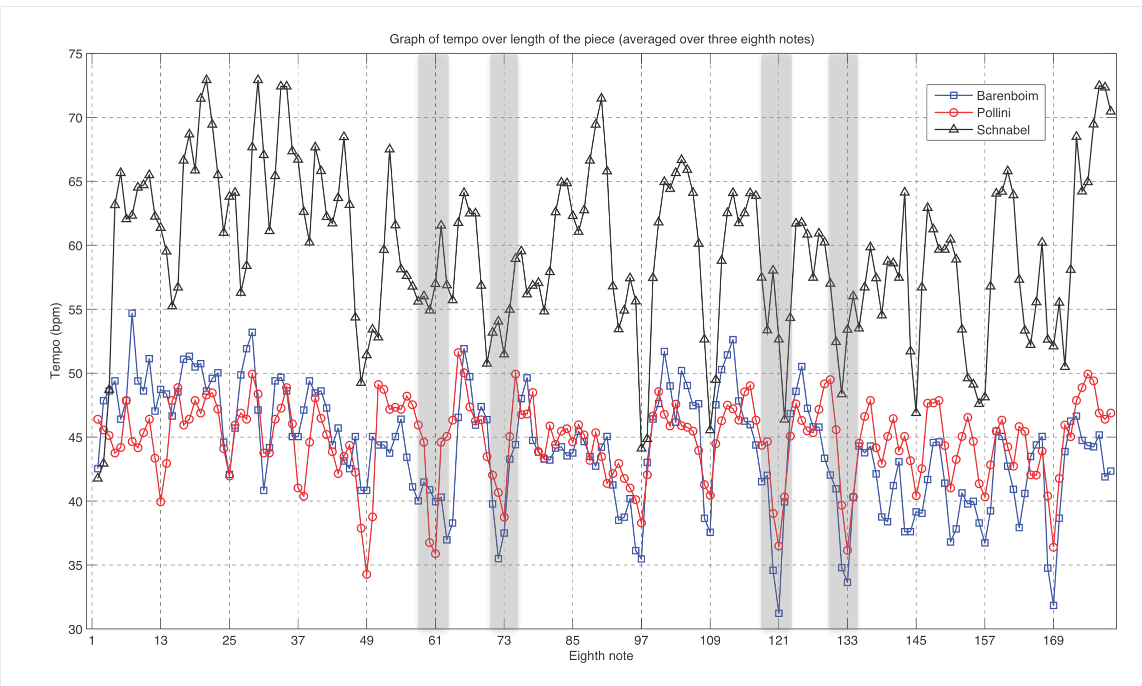


Figure 3. Tempo curves for the first fifteen bars of Beethoven's *Moonlight Sonata* performed by Barenboim, Pollini, and Schnabel (the gray bars outline the onset of the right-hand dotted rhythm motif).

Inspection of Cross-bar Line Behavior

The boundary between two adjacent phrases, the end of the previous phrase and the beginning of the next, is demarcated by a local minimum in the tempo graph. The following section inspects the locations of these local minima in the three performances. Pollini's phrasing strategy is remarkably consistent. All but one of the local minima in the tempo graph occurs on a vertical grid line (i.e. on the downbeat); in the only exception, the local minimum was at the next triplet eighth note of the bar. Figure 4b shows Pollini's tempo graph; shaded discs highlight the local minima that coincide with the downbeat, and a circle indicates the downbeat that is one before the local minimum at the 38th triplet eighth note. Thus, the performed phrase boundaries almost always occur on the downbeat, with only one exception, indicating rather strict adherence to the bar lines.

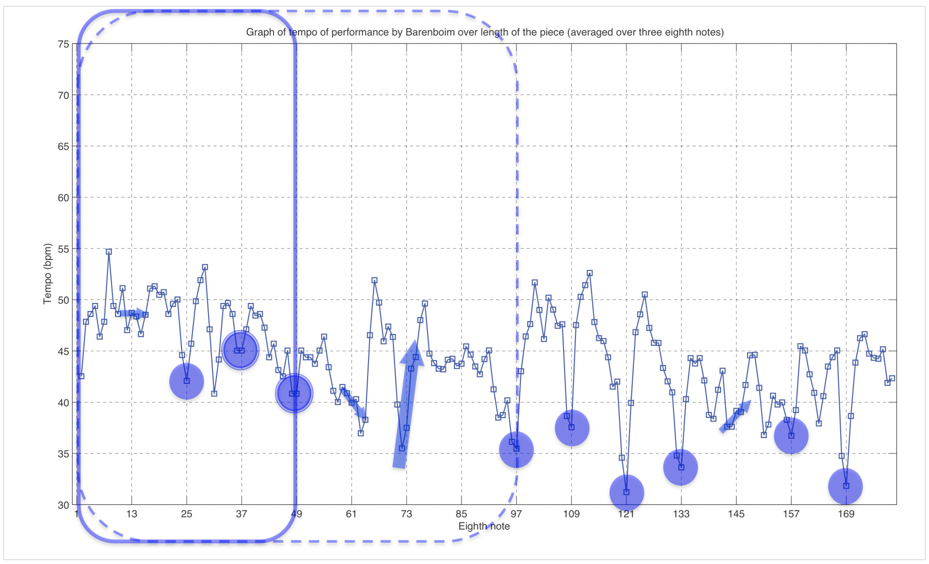
In contrast, in Schnabel's performance, the local minima in the tempo graph (the boundaries of the performed phrase groupings) seldom align with the bar line. The note at the downbeat is most often either accelerating into a new phrase (depicted by upward pointing arrows in Figure 4c), indicating that a grouping began before the bar line, or decelerating to the close of the previous phrase (depicted by downward pointing arrows in Figure 4c), indicating that the current grouping will end after the bar line.

> This is the tension between metric groups (measured, regularly recurring beat groupings) shown by the bar lines in the score, and the boundaries of figural groupings or gestures ('temporal gestalts') which are not generally shown in an unedited score. Thus, on one hand, performers must find the figural or phrasing groups hidden in the score and on the other, intuitively musical players must learn to overcome the seductive appearance of the bar lines which do not represent their natural feel for the gestural grouping of music (Bamberger, 2011, p. 94).

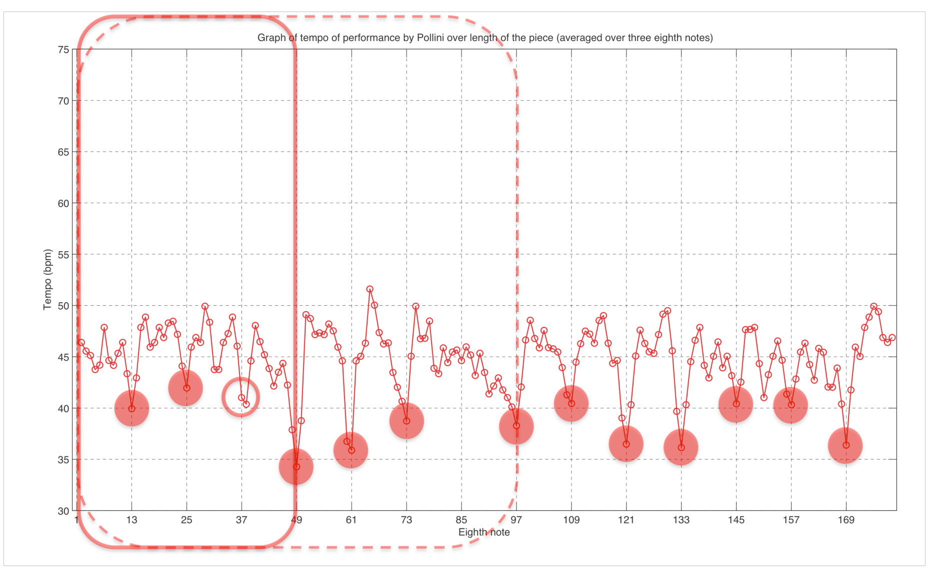
Focusing on the first half of the example (the first through the 97th triplet eighth notes), the first performed phrase boundary to align with a bar line occurs at the 97th triplet eighth note (marked by the first shaded disc in Figure 4c). This first downbeat phrase boundary coincides with the arrival in the new key of E major (relative major to C-sharp minor, the key of the piece), placing special emphasis on this tonal change. There is a secondary local minimum at the downbeat at the 73rd triplet eighth note (marked by a gray circle), but it is superseded by the lower local minimum in the previous triplet, which points to a more significant boundary at the start of the dotted rhythm motif in the right hand melody. This point shall return in the discussion on the right hand dotted rhythm motif.

Moving on to the second half of the example, the next downbeat phrase boundaries in Schnabel's performance occur at the switch to E minor a bar later (at the 109th triplet eighth note), and at the first introduction to the key of B minor three bars following that (at the 145th triplet eighth note). Another secondary local minimum occurs at the downbeat on the 169th triplet eighth note, but that is trumped by the next local minimum (two eighth notes later) that launches into the next phrase as the B minor triplet morphs into B major. Thus, Schnabel's performed phrase boundaries coincide with the bar lines only when they mark significant structural tonal changes. Otherwise, the constant ebb and flow across the bar lines creates a sense of continuity, perhaps a clue as to how he created these long, long lines, which will be further addressed in the next section.

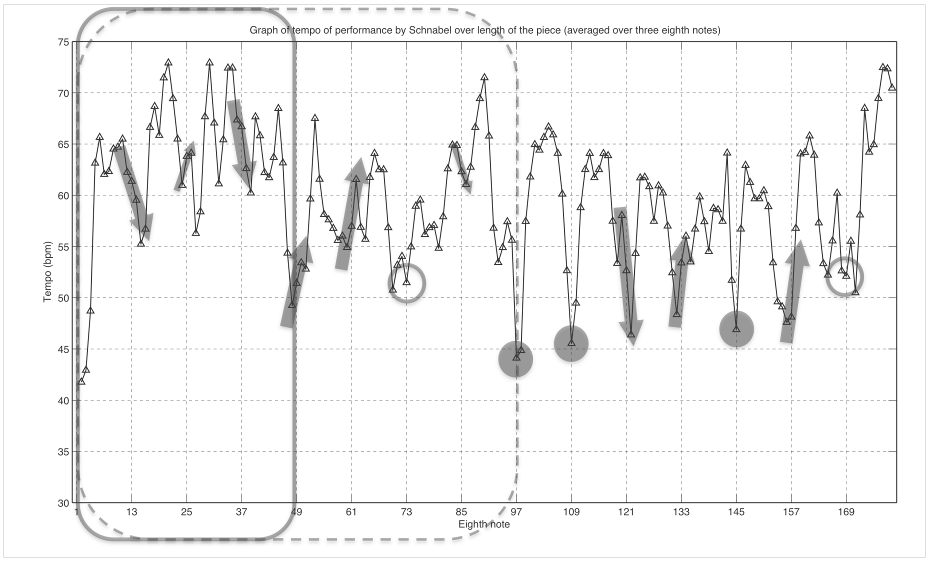
Barenboim's performance has some of the downbeat phrase boundary features of Pollini's and the across-the-bar line acceleration/deceleration of Schnabel's performance, as shown in Figure 4a. An interesting feature of Barenboim's performance is the sustained nature of the local minima at the 36th-37th and 48th-49th eighth notes (indicated by double-lined shaded discs in the figure). By elongating the locally slowest tempo, he places particular emphasis on the cadence at the end of the first phrase in the music.



a) Barenboim



b) Pollini



c) Schnabel

Figure 4. Direction of tempo trajectories at the beginnings of each bar.

Large-scale Phrase Arcs

We return at this point to Bamberger's observations. When re-visiting the recordings recently, Bamberger (2010) explains:

> the thing that stands out in the Schnabel performance is his almost mysterious ability to create or to project a 'long line' when the piece is basically slow-moving to static. What I mean by 'mysterious' is that trying to account for how that whole first phrase (even though only 4 bars long) is as if in one long breath. The other performers seem to stop at each bass note, with the right hand just embellishing it, but not make it move, even in its stasis. But if you try to listen for particular aspects–dynamics, rubato, balance–I, at least, can't say what he does to make that long breath happen. As he used to say, if you can HEAR it, you can make it happen. It's a kind of concentration, never letting the bass line (which couldn't be more banal–a sort of ordinary 'walking bass') stop.

While it may be difficult to listen to the differences, it is possible to tease out meaningful systematic variations in tempo and dynamics with the help of a computer. Earlier discussion involved one of Schnabel's strategies for creating long lines: to only align phrase-grouping boundaries with the downbeat when projecting a significant tonal change. Another performance strategy that leads to this perception of a long phrase is apparent in the overall arch of the tempo graph. Figure 5 shows two high-level phrase arcs (eighth note counts 1-48, which is bounded by the solid line box in Figure 5, and 48-97) in Schnabel's performance of *Moonlight Sonata*. Barenboim's performance traces a similar, but more modest, tempo arc to Schnabel's first performed phrase, and Pollini's performance traces a similar tempo arc to Schnabel's second performed phrase.

Underlying these large-scale gestures are smaller scale phrase arcs (lower-level groupings) observable in the tempo graph. The tempo at the beginning of the first large phrase arc is 42 bpm (rounded to the nearest integer) and that at the end of the second is 44 bpm; at the boundary between these two phrases, the tempo is 49 bpm. Based on this fact, together with the general shape of the tempi in between, one could infer an even higher-level grouping based on a larger arc from the first to the 97th eighth note (inside the boundaries of the dotted line box in Figure 5).

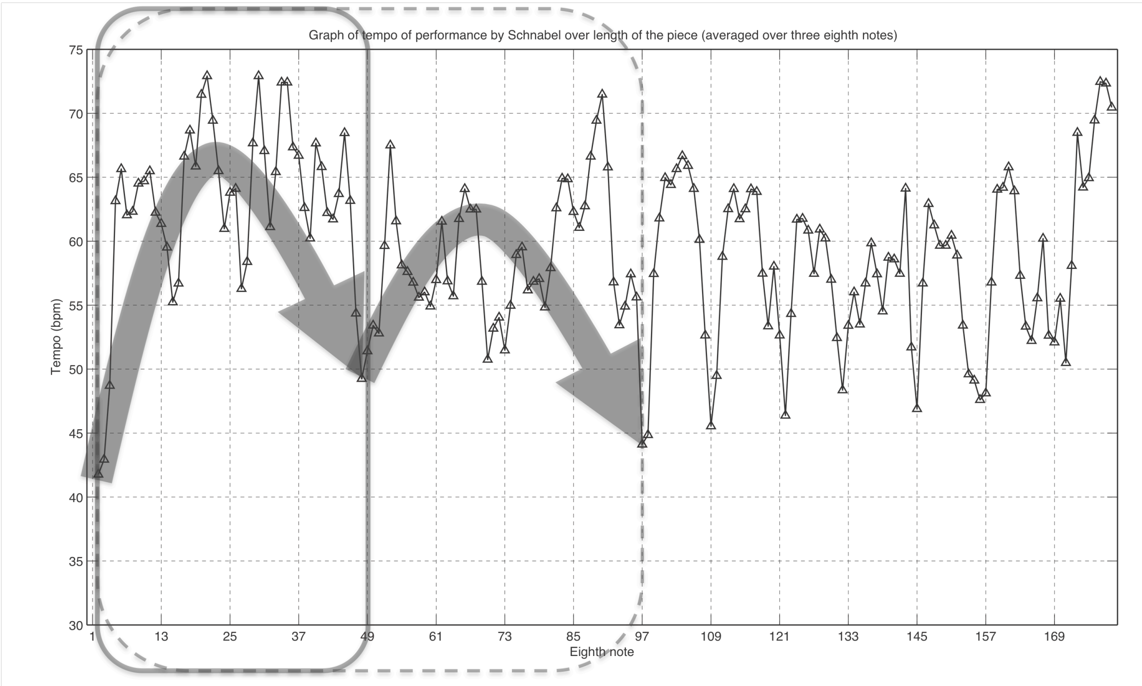


Figure 5. High-level phrase arcs in Schnabel's performance of Beethoven's *Moonlight Sonata*.

Agogic Accents in the Bass Line

The prominence of the bass line in Schnabel's recording is also created through the use of agogic accents, the stretching of time at the beat on which the bass note occurs, which result in dips in the tempo graph. In Figure 6, Schnabel's tempo graph is annotated with gray bars that denote the beats in which bass note onsets occur, and gray discs mark local tempo minima corresponding to these beats. Every bass note onset has a corresponding tempo dip with the exception of those at eighth note numbers 61, 133, 151, and 157. Referring back to the score in Figure 1, {133, 151, 157} are part of sequences of three consecutive on-beat events, for which agogic accents on every bass note would be less than effective. {61, 133} are also part of the right-hand dotted rhythm motif, which brings us to observation (2).

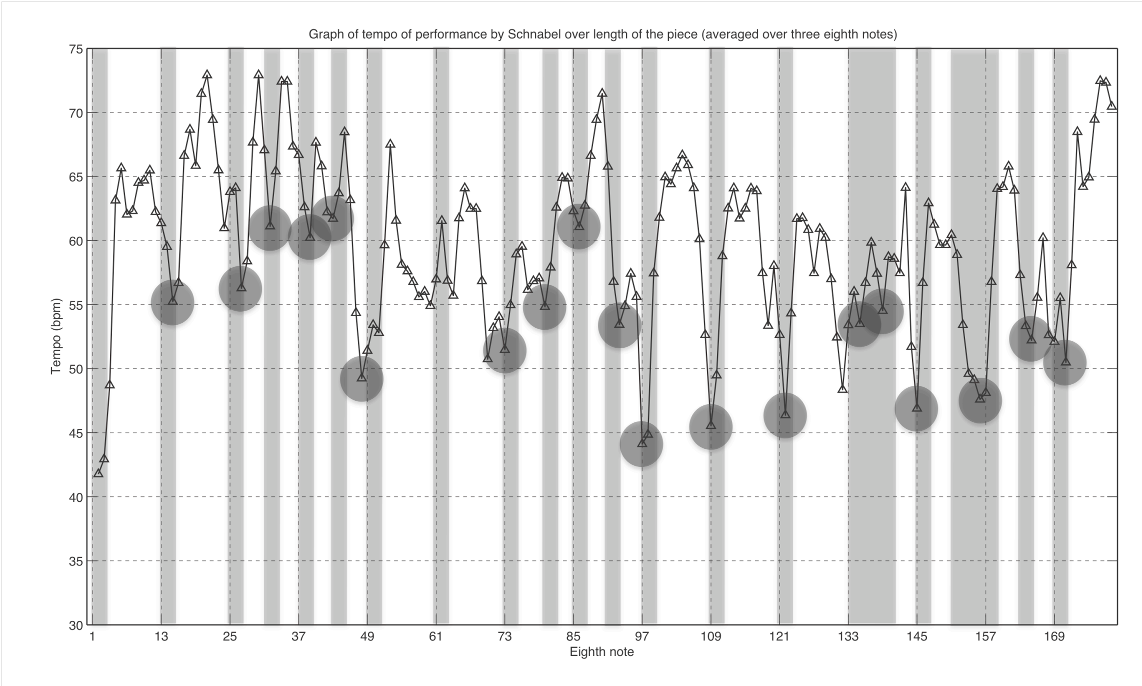


Figure 6. Tempo graph of Schnabel's performance of Beethoven's *Moonlight Sonata* with gray regions denoting beats with bass line note onsets, and shaded discs marking tempo minima in these beats.

Emphasis on Right-hand Dotted Rhythm Motif

The two-beat span of each occurrence of the right hand dotted rhythm motif is highlighted in Figure 3. Pollini's and Barenboim's performances sport significant tempo dips in these regions; they put particular stress on the downbeat of the motif either by stretching it or by delaying its onset. While Schnabel's performance also has tempo dips in these regions, the primary local minimum (lowest tempo achieved) in each case never occurs on the downbeat. Furthermore, within each shaded region, the tempo dips are invariably accompanied by local tempo peaks, which point to local figural groupings. In Bamberger's (2010) words:

> As for the 'signature dotted rhythm,' he plays the 16ths perhaps a bit more slowly and melodically than the others, but again going not so much to the downbeat as keeping the downbeat fluid, itself going on–probably because of the way he handles the bass accompaniment–but always in the background. I notice, too that he emphasizes the A (in bar 7) again making it function as an upbeat moving forward. The whole passage is marked: *com initimissimo sentimento, sempre quasi improvisato, ma molto simplice, non patetico.* So, like I said, you have to imagine it first, then you will find how to do it. But it certainly is all about the long line and, as Roger Sessions always said, the details make the long line and the long line gives meaning to the details.

The A in bar 7 occurs on the 79th triplet eighth note. Schnabel's graph in Figure 3 indeed shows a temporary dip at 80 before accelerating ahead. Thinking of such secondary minima (of which there are many, not only in the highlighted region with the right-hand dotted rhythm) as "upbeats moving forward" opens up another explanation for how Schnabel sustains the long lines in his performance.

Two Student Projects

The students in the Musical Prosody and Interpretation class are required to design a final project related to the class topic. The project can be an implementation of some part of a paper assigned in class or an original project inspired by the readings. This section presents two projects related to variations in expressive performance, demonstrating how the students use technical tools and methodology to answer the musical questions they pose, and how, by interacting with the results of their analyses, they arrive at musically interesting conclusions.

Guitar vs. Piano Performances of Granados' *Danza Española No. 5*

The first project is by Chandrasekhar Rajagopal (2010), a masters student of electrical engineering who had completed a bachelor's degree also in electrical engineering with a minor in music performance (guitar). He has played classical guitar for 14 years and has served as composer/arranger for USC's South Asian a cappella team.

Rajagopal (2010) was interested in the following questions: (1) whether a performer's instrument constrains the expressive choices in an interpretation; and (2) whether there are universal understandings of a piece that translate to prosodic choices that are invariant across instruments. He chose to focus his study on Enrique Granados' *Danza Española No. 5*, a piano work that has become a standard in the guitar canon. He studied six piano recordings, and six guitar recordings, including one of a guitar duo. Using the method described earlier in this paper, he annotated the beats using Sonic Visualiser (Canam, Landone, & Sandler, 2010), calculated the instantaneous tempi using three-beat smoothing, and graphed the results as shown in Figure 7. The graphs show the tempo curves for the first A-B sections of this ternary form (A-B-A) piece. The x-axis is indexed by beat number, and 187 marks the beginning of the B section. For ease of comparison, all performance data were normalized to the same global tempo, the mean across both instruments and all performances.

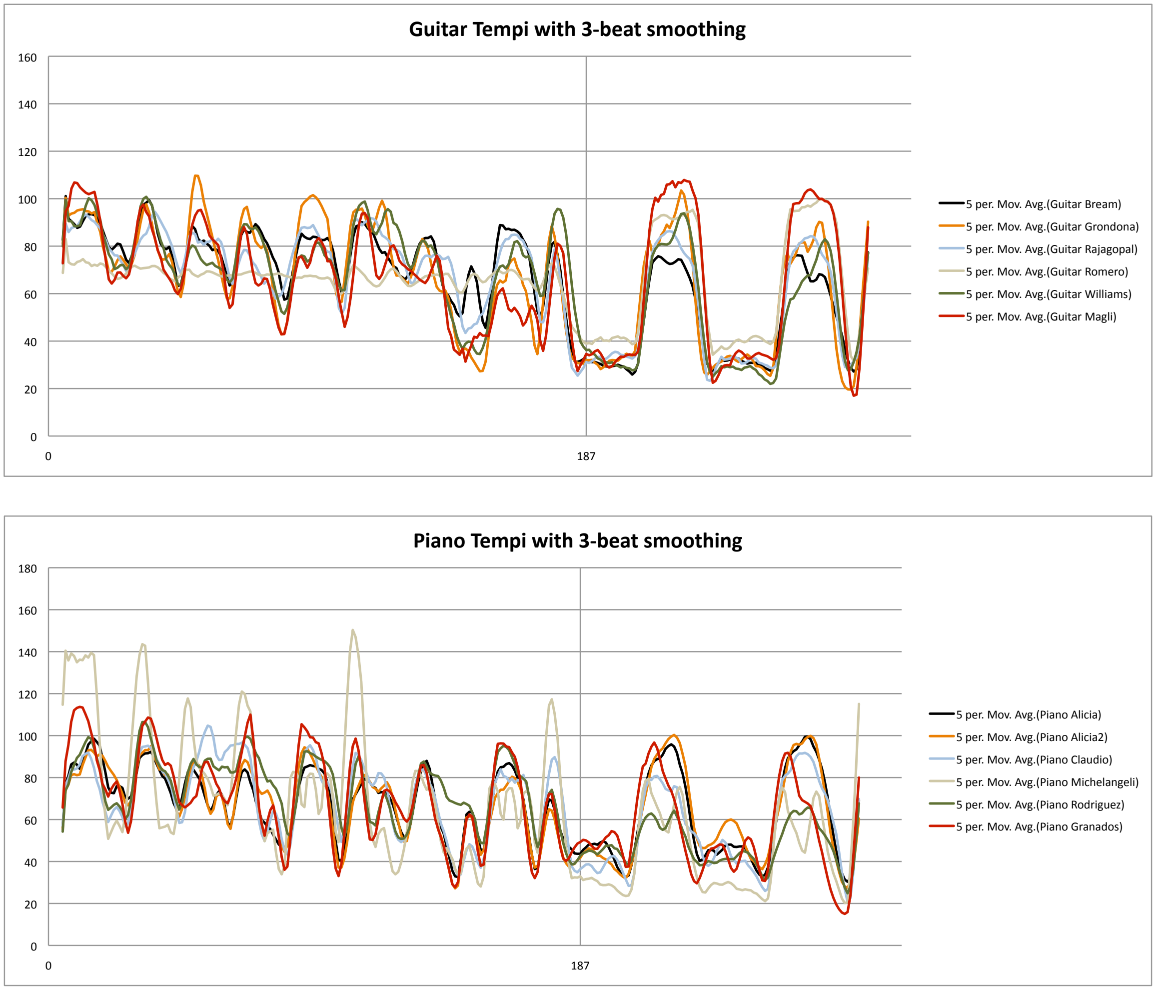


Figure 7. Tempo graphs of pianists' and guitarists' rendering of Granados' *Danza Española*.

Comparing the average tempo graphs for each instrument, Rajagopal (2010) writes,

> It is clear that there are similarities between the two profiles. The pattern of peaks and troughs in both piano and guitar performances in the **A section** (though more prominent in the case of pianists), strongly suggests **tempo modification to suit phrasal structure**. Closer inspection reveals that the ebbing and flowing of tempo in that section coincides closely with **4 bar phrases** in the Danza. In the **B section**, the two profiles are strikingly close in shape, only varying in the tempo offset (Instantaneous tempo section, para. 4).

Observing a general downward trend in the tempo, Rajagopal (2010) confirms it by graphing the tempo calculated with a 25-beat smoothing window. The downward slope cannot be explained entirely by the B section being slower than the A section. Rajagopal (2010) postulates that a performer might slow down in the A section for the following reasons:

- For the listener: To ease the transition from a faster section to a slower one
- For the performer: The piece is merely starting at too fast a pace, and once the **difficulties of performing** it are 'remembered', **the pace has to slow down to accommodate for accuracy**. **This is unlikely** - 10 out of the 12 performances are concert-level performances …
- Subconsciously: The performer, without realizing it, **adjusts the tempo gradually over time in anticipation** of the slower section (Global tempo section, para. 3).

He quickly eliminates the second reason by pointing out that the Romero duo's performance shows the same tempo decline in spite of the fact that the two-guitar arrangement eliminated many of the physical challenges of playing the piece. Rajagopal (2010) then addresses specific differences between the pianists' and the guitarists' tempo profiles by comparing the instrument-specific difficulties of playing the same passage – the physical challenges of playing a passage can interfere with the expression of phrase structure. Finally, he concludes that

> the prosodic techniques employed by musicians are a function of:
>
> - the limitations of the instrument (for instance the guitarist's difficulty in shifting position quickly); and,
> - the idiomatic styles associated with the instrument (for instance the pianist's staccato resulting in time delays; Rajagopal, 2010, Conclusion section, para. 1).

Thus, the physical constraints of playing a particular instrument directly affect the musician's ability to convey phrase structure.

> Guitarists typically assign specific hand placement and fingering locations based on the ease of performance – the hope is that an 'easier' arrangement allows for technical efficiency. This project's discovery places even more importance on correct fingering, given that it now has an effect on the ability to convey musical expression (Rajagopal, 2010, Conclusion section, para. 2).

Evolution of Violin Vibrato

The second project is by Balamurali Ramasamy Govindaraju (2010), a Masters student in Electrical Engineering. Govindaraju has not had formal musical training, but is an avid classical music lover. He has observed that recordings of the same piece decades apart sound significantly different and is interested in formalizing styles in violin playing over time to see if there is a trend to these changes. In particular, he chose to focus on the study of vibrato.

Govindaraju (2010) chose to analyze two selected long notes in performances of a Baroque piece, the Adagio from J. S. Bach's *Violin Sonata No. 1 in G Minor*. The nine performances he studied ranged from Joachim's 1904 recording to Lansdale's 2002 recording. Govindaraju (2010) extracted corresponding segments of music from each performance using the MATCH plugin in Sonic Visualiser (Canam, Landone, & Sandler, 2010) for analysis. He then tracked the pitch modulations using the freely available speech analysis software, PRAAT (Boersma & Weenink, n.d.). He computed the minimum, maximum, and mean frequencies, and the standard deviation of the frequency modulation. The results for the first excerpted note are graphed in Figure 8, and Govindaraju (2010) writes:

From the analysis it was evident that, at the start of the 20th century vibrato was rarely employed. In the 1920's the occurrence of vibrato was a little more prevalent but it was very uneven. Each cycle of the vibrato seemed to change with time. The amount of modulation induced in the vibrato increased in the 1930's and 40's. Yehudi Menuhin topped [the chart] with a standard deviation of 3.38 Hz from the note's [fundamental frequency]. From here on there seems to be a decreasing trend in the use of vibrato, which is evident from the standard deviation values of the vibrato except for Itzhak Perlman's 1987 performance. The performance made in 2002 by Katie Lansdale and Gidon Kremer have very little or no vibrato at all (Results and discussion section, para. 3).

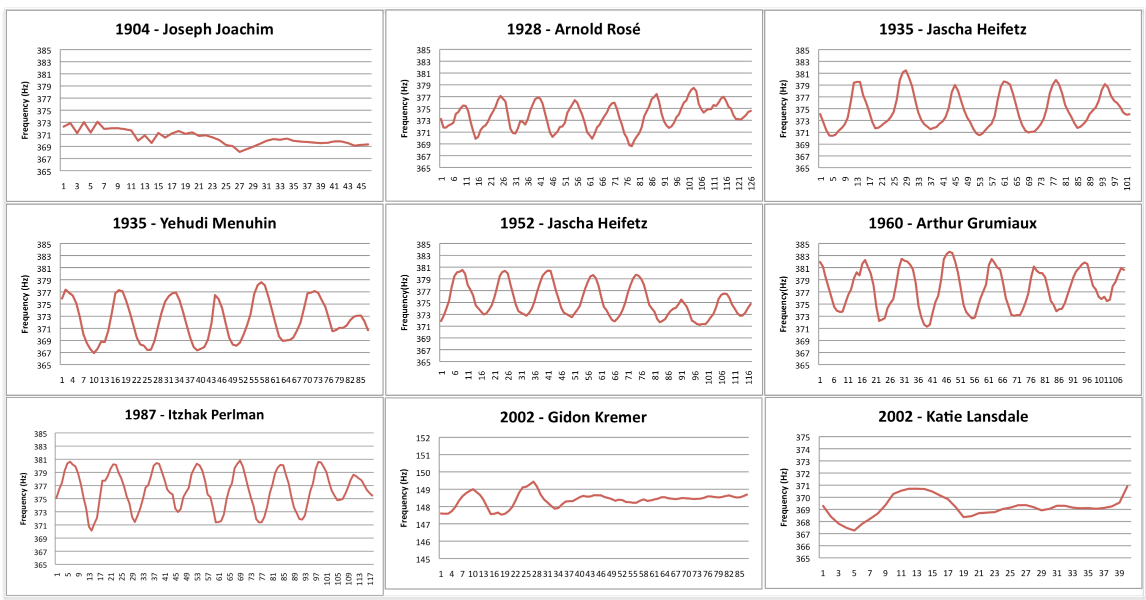


Figure 8. Graphs of frequency modulation over the same held note in recordings of the *Adagio* from Bach's *Violin Sonata No. 1 in G Minor*.

In short, the study of the one held note showed little vibrato in 1904; when vibrato enters the scene, it is first a little uneven, then increases in amplitude, and eventually develops a shape of its own, an envelop to the cycles; then, in 2002, vibrato appears to have faded into oblivion again (Govindaraju, 2010). Govindaraju (2010) performed an analysis of a longer held note in the same piece, and drew the following conclusion:

> For the second analysis a longer vibrato clip was chosen from each piece. This time the standard deviation was higher for every performer than the first analysis. Here also the occurrence of vibrato was found to be less in the old recordings. The amount of modulation increased like it did in the first analysis with time. In both the cases Yehudi Menuhin topped [the chart] with the highest amount of modulation. Like in the first analysis, there was a decrease in the amount of modulation after [the] 1960's except for Itzhak Perlman's 1987 performance (Results and discussion section, para. 5).

While Govindaraju (2010) concedes that more data is needed to confirm the observation, he offers some suggestions for future work:

> The current analysis mainly concentrates on the pitch modulations caused by vibrato. But psychoacoustic researches have shown that we are more sensitive to amplitude modulations in the vibrato than the frequency modulation of the pitch. It will be worth looking into the power spectrum associated with the fundamental frequency of the note. From this we may be able to analyze the amplitude modulation occurring due to the vibrato and also the dynamics during the vibrato (Future work section, para. 1).

Conclusions

Engineering tools for quantifying and tracking the evolution of musical parameters have opened new avenues for scientific study of performances. Holding still some aspect of an entire performance in a graph allows for examination of patterns in detail that may not be apparent when hearing the music in time. Many of the tools for annotating and quantifying performance are now freely available for widespread use in music scholarship. They can be extremely useful in illustrating concepts on music cognition and performance, as evidenced by the Schnabel example. Simply by superimposing the bar lines on the tempo graph, one can see immediately the lack of correspondence between Schnabel's grouping (phrase) boundaries and the bar lines, providing a clue as to how he creates the perception of long lines in slow music that could be static. These tools also facilitate the teaching of performance research studies, enabling students to pose questions based on their own intuitions to design experiments to test their hypotheses and discover truths about performance.

References

Bamberger, J. (2010). *What is time – A hearing is a performance, a performance is a hearing*. Guest lecture, Andrew and Erna Viterbi School of Engineering, University of Southern California, Los Angeles, CA.

Bamberger, J. (2011). The collaborative invention of meaning: A short history of evolving ideas. *Psychology of Music, 39*(1), 82-101.

Beethoven, L. V. (1987). Piano Sonata No. 14 in C Sharp Minor, Op. 27 No. 2, "Moonlight": I. Adagio sostenuto (Recorded by D. Barenboim). On *Beethoven: Moonlight, Pathétique & Appassionata Sonatas* [CD] Hamburg, Germany: Deutsche Grammophon GmbH.

Beethoven, L. V. (1992). Piano Sonata No. 14 in C Sharp Minor, Op. 27, No. 2, "Moonlight": I. Adagio sostenuto [Recorded by M. Pollini]. On *Beethoven Piano Sonatas: Moonlight & Pastorale* [CD], Hamburg, Germany: Deutsche Grammophon GmbH.

Beethoven, L. V. (2009). Piano Sonata No. 14 In C Sharp Minor Op. 27 No. 2 "Moonlight" : I. Adagio Sostenuto [Recorded by A. Schnabel]. On *Artur Schnabel* [CD] United Kingdom: EMI Records Ltd.

Boersma, P. & Weenink, D. (n.d.). *Praat: doing phonetics by computer.* Retrieved from http://www.fon.hum.uva.nl/praat

Cannam, C., Landone, C., & Sandler, M. (2010). Sonic Visualiser: An open source application for viewing, analysing, and annotating music audio files. *Proceedings of the ACM Multimedia 2010 International Conference,* (October 2010). Firenze, Italy.

Cheng, E. & Chew, E. (2008). Quantitative analysis of phrasing strategies in expressive performance: Computational methods and analysis of performances of unaccompanied Bach for solo violin. *Journal of New Music Research, 37*(4), 325-338.

Chew, E. (2006). Imparting knowledge and skills at the forefront of interdisciplinary research – A case study on course design at the intersection of music and engineering. *Proceedings of the 36th ASEE/IEEE Frontiers in Education Conference*, (Oct 27-31, 2006), 27-32. San Diego, CA.

Chew, E. (2010, January). Topics in engineering approaches to music cognition [Course syllabus, University of Southern California]. Retrieved from http://www-scf.usc.edu/~ise575

Chuan, C.-H. & Chew, E. (2007). A dynamic programming approach to the extraction of phrase boundaries from tempo variations in expressive performances.

Proceedings of the 8th International Conference on Music Information Retrieval, (Sep 23-27, 2007). Vienna, Austria.

Dixon, S. (2001). Automatic extraction of tempo and beat from expressive performances. *Journal of New Music Research, 30*(1), 39-58.

Dixon, S., Goebl, W., & Widmer, G. (2002). Real-time tracking and visualisation of musical expression. In C. Anagnostopoulou, M. Ferrand, A. Smaill (Eds.), *Music and artificial intelligence - Second international conference, ICMAI 2002, Edinburgh, Scotland, UK, September 12-14, 2002, proceedings. Springer lecture notes in computer science/lecture notes in artificial intelligence, 2445* (pp. 58-68). Springer.

Gabrielsson, A. (1999). Music performance. In D. Deutsch (Ed.), *The psychology of music* (2nd ed.) (pp. 501-602). San Diego, CA: Academic Press.

Govindaraju, B. R. (2010). *Analysis of differences in violin performances over time*. Unpublished manuscript, Hsieh Department of Electical Engineering, University of Southern California, Los Angeles, California. Retrieved from http://www-scf.usc.edu/~ramasamy/index.html

Palmer, C. (1997). Music performance. *Annual Review of Psychology*, 48, 115-38.

Rajagopal, C. (2010). *Expressive instruments - from Spanish piano music to the Spanish guitar*. Unpublished manuscript, Hsieh Department of Electical Engineering, University of Southern California, Los Angeles, California. Retrieved from http://www-scf.usc.edu/~crajagop/projects.html

Appendix A: Week-by-week details for Musical Prosody and Interpretation

Introduction	
Week 1	Introduction to the course, and to concepts of beat, tempo, and loudness.
(Jan 12)	Listening examples include: Kreisler, Bach's Unaccompanied Violin Sonata, Glenn Gould's recordings of Bach's Goldberg Variations, Brahms' Hungarian Dances.
Week 2	Palmer, C., & Hutchins, S. (2006). What is musical prosody? In B. H. Ross (Ed.), Psychology of Learning and Motivation, 46: 245-278.
(Jan 19)	Homework 1B: Bring a piece of music that has variations in tempo or loudness to share with the class. Download and install QMUL's Sonic Visualiser.
Rhythm in Music and Speech	
Week 3	Patel, A.D., Iversen, J.R., & Rosenberg, J.C. (2006). Comparing the rhythm and melody of speech and music: The case of British English and French. Journal of the Acoustical Society of America, 119:3034-3047.
(Jan 26)	Iversen, J.R., Patel, A.D., & Ohgushi, K. (2008). Perception of rhythmic grouping depends on auditory experience. Journal of the Acoustical Society of America, 124: 2263-2271.
	Patel, A.D. (2006). Musical rhythm, linguistic rhythm, and human evolution. Music Perception, 24:99-104.
(Jan 28)	Special Event: Attend the talk by Aniruddh Patel to take place at 3:30pm in Doheny 240 - *Rhythm in Speech and Music*.
Beat and Tempo: Tracking and Analysis	
Week 4	Dixon, S. (2001). Automatic Extraction of Tempo and Beat from Expressive Performances. Journal of New Music Research, 30(1):39-58.
(Feb 2)	Download Dixon's BeatRoot software (requires Java 1.5 or higher). Beat tracking examples.
	Dixon, S. & Widmer, G. MATCH: A Music Alignment Tool Chest. In Proceedings of the 6th Intl Conf on Music Information Retrieval, London, UK, 492-497.
	Download Dixon's MATCH software (Java, any platform), or the Sonic Visualiser MATCH Vamp plugin.
Week 5	Timmers, R., Ashley, R, Desain, P, and Heijink, H. (2000). The influence of musical context on tempo rubato. Journal of New Music Research 29(2):131-158.
(Feb 9)	Cammuri, A., Mazzarino, B., Ricchetti, M., Timmers, R., and Volpe, G. (2004). Multimodal Analysis of Expressive Gesture in Music and Dance Performances. In Gesture-Based Communication in Human-Computer Interaction, Springer Lecture Notes in Computer Science 2915. Read the Introduction (p.20-22), Section 4 (p.30-37).
	Timmers, R. (2005). Predicting the similarity between expressive performances of music from measurements of tempo and dynamics. Journal of the Acoustical Society of America, 117(1): 391-399.
Tempo and Loudness: Visualization	
Week 6	Langner J. & Goebl W. (2003). Visualizing Expressive Performance in Tempo-Loudness Space. Computer Music Journal, 27(4): 69-83.
(Feb 16)	Goebl, W., Pampalk, E. & Widmer, G. (2004). "Exploring Expressive Performance Trajectories: Six Famous Pianists Play Chopin Pieces." In Proceedings of the 8th International Conference on Music Perception and Cognition.
Week 7	Grachten, M., Goebl, W., Flossmann, S., Widmer, W. (2009). Phase-plane Representation and Visualization of Gestural Structure in Expressive Timing. Journal of New Music Research, 38(2): 183-195.
(Feb 23)	Sapp, C. S. (2007). Comparative Analysis of Multiple Musical Performances. In Proceedings of the 8th International Conference on Music Information Retrieval.
	Sapp, C. S. (2008). Hybrid Numeric/Rank Similarity Metrics for Musical Performance Analysis. In Proceedings of the 9th International Conference on Music Information Retreival.
	Spiro, D., Gold, N, Rink, J. (2008). Plus Ça Change: Analyzing Performances of Chopin's Mazurka Op. 24 No. 2. In Proceedings of the 10th International Conference on Music Perception and Cognition.
Rhythm and Timing	
Week 8	Collier, G. L. and Collier, J. L. (2002). A Study of Timing in Two Louis Armstrong Solos. Music Perception, 19(3): 463-483.
(Mar 2)	Wright, M., Schloss, W. A., Tzanetakis, G. (2008). Analyzing Afro-Cuban Rhythm Using Rotation-Aware Dynamic Programming. In Proceedings of the International Conference on Music Information Retrieval.
	Benadon, F. (2009). Time Warps in Early Jazz. Music Theory Spectrum, 31(1): 1-25.
Week 9	Friberg, A., and Sundstrom, A. (2002). Swing Ratios and Ensemble Timing in Jazz Performance: Evidence for a Common Rhythmic Pattern. Music Perception, 19(3): 333-349.
(Mar 9)	Lindsay, K. A. and Nordquist, P. R. (2006). A technical look at swing rhythm in music. Journal of the Acoustical Society of America, 120(5): 3005.
	Dixon, S. and Gouyon, F. (2004). Towards Characterisation of Music via Rhythmic Patterns. In Proceedings of the International Conference on Music Information Retrieval.
Highlights: Accents and Stress	
Week 10	Guest Speaker: Jeanne Bamberger on Performance, "What is Time - a hearing is a performance, a performance is a hearing"
(Mar 25)	Bamberger, J. (2006). What Develops in Musical Development? A View of Development As Learning. In G. MacPherson (ed.) The child as musician: Musical development from conception to adolescence. Oxford, U.K. Oxford University Press.
	Examples: Moonlight Sonata Adagio by Barenboim, Pollini, Schnabel, Gould, Ashkenazy; Bach Cello Suite No. 2 (Gigue) by Casals, Ma.
Week 11	What is musical accent or stress?
(Mar 30)	Parncutt, R. (2003). Accents and expression in piano performance. In K. W. Niemoller (Ed.), Perspektiven und Methoden einer Systemischen Musikwissenschaft (Festschrift Fricke) 163-185. Frankfurt/Main, Germany: Peter Lang.
	Pfordresher, P. Q. (2003). The Role of Melodic and Rhythmic Accents in Musical Structure. Music Perception, 20(4): 431-464.
Week 12 (Apr 6)	Project updates. Presentation on McGill Music Technology Program by Jordan Smith.
Week 13	Parncutt, R. (2003). Modelling durational accent in musical rhythm. In Proceedings of the 5th Triennial ESCOM Conference, 339-343.

	Drake, C., Palmer, C. (1993). Perceptual and performed accents in musical sequences. Bull. Psychonomic Soc. 31:107-10.
Phrasing / Grouping	
(Apr 15)	Penel, A., Drake, C. (2004). Timing variations in music performance: Musical communication, perceptual compensation, and/or motor control? Perception & Psychophysics, 66(4): 545-562.
	Cheng, E., and Chew, E. (2008). Quantitative Analysis of Phrasing Strategies in Expressive Performance: Computational Methods and Analysis of Performances of Unaccompanied Bach for Solo Violin. Journal of New Music Research, 37(4): 325-338.
Week 14	MacRitchie, J., Buck, B., Bailey, N. J. (2009). Visualizing Musical Structure through Performance Gesture. Proceedings of the 10th International Society for Music Information Retrieval Conference, 237-242.
(Apr 20)	Raphael, C. (2009). Symbolic and Structural Representation of Melodic Expression. Proceedings of the 10th International Society for Music Information Retrieval Conference, 555-560.
Ensemble Coordination	
Week 15	Jaffe, D. (1985). Ensemble Timing in Computer Music. Computer Music Journal, 9(4): 38-48.
(Apr 27)	Maduell, M., and Wing, A. M. (2007). The dynamics of ensemble: the case for flamenco. Psychology of Music, 35:591-628.
	Chew, E., Sawchuk, A., Tanoue, C., Zimmermann, R. (2005). Segmental Tempo Analysis of Performances in Performer-Centered experiments in the Distributed Immersive Performance Project. In Proceedings of International Conference on Sound and Music Computing.
	Bartlette, C., Headlam, D., Bocko, M., Velikic, G. (2006). Effect of Network Latency on Interactive Musical Performance. Music Perception, 24(1): 49-62.
Final Projects (May 11)	

Appendix B: Students’ Final Projects for Musical Prosody and Interpretation

Analysis Tools

Automatic Extraction of Expressive Timing Using Dynamic-time-warp Alignment of Score and Performance by Brian Highfill
Timing dynamics of musical performance is an important aspect of musical prosody. Tempo rubato is popularly used as a metric to analyze this type of musical expression. This is extracted most accurately from the manual annotation of note onsets times and is cumbersome and impractical for batch processing. This project aims to solve the problem for pieces with known score by automatically aligning a recorded performance to a synthesized MIDI representation following the dynamic time-warping approach of the MATCH algorithm.

Western Instrumental Music

Analysis of Glissando Characteristics in Trumpets and Trombones by Abhijit Bhattacharjee
The **automatic identification of musical instruments** in an audio file is among the most difficult tasks in **music information retrieval** (MIR). One of the most serious challenges in automatic instrument identification is when two instruments **sound very similar** to each other. Here, I have chosen to focus on analyzing the distinguishing differences between **trumpets and trombones**, by analyzing the glissando present between note or pitch transitions in musical performances. My hope is that this characteristic can be used in a machine algorithm to increase classification performance significantly.

Expressive Instruments - from Spanish Piano Music to the Spanish Guitar by Chandra Rajagopal
Much work has recently been done on musicians' use of expressive timing to communicate musical ideas - minor fluctuations in tempo to convey expression. This project will explore how the motivations, challenges and execution differ for contrasting instruments. 12 performances of Enrique Granados' Spanish Dance no.5 on Classical Guitar and Solo Piano will be analyzed for this purpose - the work was originally written for solo piano, but has since gained great popularity for its guitar transcription.

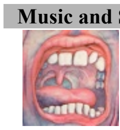
Analysis of Differences in Violin Performances Over Time by Balamurali Ramasamy Govindaraju
Music like every other thing has gone through its fair share of evolution.This would have definitely contributed to the changes in the style of performance. We could certainly notice a difference in how the music sounds between performances of same piece that were performed decades apart. This project project tries to address or identify the changes in violin performances over time using signal processing techniques.

World Music

Assignment of Definite Times of Day - Rhythm Analysis in Indian Classical Music by Kamlesh Lakshminarayanan
Indian classical music tradition ascribes certain ragas to particular times of the day. This project considers music from different times of the day: morning, afternoon, evening and night and attempts to find rhythmic commonalities in each one of these groups. I seek to answer the question: Does the time theory of ragas have an impact on the way the percussionist performs?

Regional characteristics and differences of some Chinese folk music by Bo Li
This project studies characteristics and differences of some Chinese folk music based on the regional classification. Some representative folk music in one collection is analyzed. Their tempo, score intervals, and nPVI are compared. The characteristics and differences are discussed with consideration on psychological and cultural factors in specific regions.

Music and Speech



Mapping Recorded Speech to Expressive Performance by Isaac Schankler
There is a growing body of musical works in which live musicians mimic or accompany recorded speech. In almost all of these works, the musician(s) must follow the recording, restricting their expressive range. What if instead, the recorded speech could be warped in time to follow the expressive performance of a live musician? This project employs free and commercially available software to accomplish this with two musical works (Peter Ablinger's Voices and Piano and an original composition) as proof of concept.

The Rapper's Rhythm - A study on the different tempi and rubato tendencies of different rap artists by Jeremy Yuan
Rap artists strive to sound different to make themselves unique to the listener. Given a steady beat, a rap artist will weave their words along in their own fashion. In this project, I study the tempo and rubato that different artists in a collaboration song use on their words. The beat may be constant, but the verse delivery most definitely is not.

Music and Video/Film

Music to Dance - Correlating Different Performances by Ravi Nitin Balajee
Dance to music. Dance steps are choreographed to suit the music being played. Different music might share a similar rhythmic pattern. In this project, I study the patterns in music using tools used in class and try to match different music to a given dance performance. That is, match Music to Dance. I intend to provide the part of music that best matches with the dance. I am using videos of dance performances on YouTube for this project.

Analysis of Fantasy Genre Film Scores by Wesley Yeh
This project explores the relationship between movie soundtracks and its corresponding scene. I analyze scores within the same film, and between films and composers, through subjective interpretation and technical analysis of tempo and loudness.