MuSA.RT and the Pedal: The Role of the Sustain Pedal in Clarifying Tonal Structure

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ABSTRACT

Pianists use the sustain pedal to clarify and project tonal structure in performance. The effect of sustain-pedal use on the projected tonal structure, while potentially useful to piano pedagogy and automated transcription, remains a little-studied phenomenon. Our goal is to discover ways to model and measure, quantitatively, the effect of the sustain pedal on tonal coherence. We use the MuSA.RT system for tonal analysis and visualization to capture the tonal patterns analyzed from a pianist's performance of Bach's Prelude No. 1 from *The Well-Tempered Clavier*, paced by a metronome, with and without the use of the sustain pedal. The analysis is based on the Spiral Array Model, as implemented in MuSA.RT. Tonal contexts are mapped to short-term and long-term centers of effect (CEs) that trace out spatial trajectories over time. The likelihood of a triad/key is given by the distance between the short-term/long-term CE and that triad/key. We present quantitative results that show that increased tonal coherence in a pedaled performance can be observed as stronger likelihood of the nearest keys (i.e. shorter distances between the long-term CE and closest key), and that use of the sustain pedal results in smoother transitions to and from the nearest triads.

I. INTRODUCTION

Pianists use the sustain pedal to artfully blend or clear sonorities. The sustain pedal helps to synchronize sounds and chords, and the harmonies they generate, and serves as a tool for clarifying tonal structure, especially in music where the main notes and harmonies are often obscured by neighbor and derived notes (p.170, Sandor, 1995). Until now, knowledge about the role of the sustain pedal in clarifying tonal structure in piano performances has primarily been anecdotal. We propose and demonstrate quantitative methods to systematically study the effects of artful sustain pedal use to manipulate the perception of tonal structures. The results extend to the sostenuto pedal, which sustains selected notes.

The application with which we conduct our study is the MuSA.RT system (Chew & François, 2003, 2005), developed for analyzing and visualizing tonal structure (pitches, chords, and keys), based on the Spiral Array Model (Chew 2000). MuSA.RT's interactivity and concurrent processing of multiple data streams is enabled by François' software architecture style (2004). The system's real time, interactive nature allows it to be deployed in live performance. Because interpretation and timing of notes never occur the same way twice in performance, MuSA.RT presents opportunities for researchers and listeners to examine, visually and quantitatively, the role of expressive performance in manipulating the perception of tonal structures over time. Its latest incarnation, MuSA.RT Opus 2.7, has the capability of capturing pedal effects.

Our goal is to quantitatively study and see the effect of sustain pedal use, and its role in clarifying tonal structure, in expert music performances. We systematically measure and analyze the results of sustain pedal use so as to understand its effect on both the performer - the ways it affects interpretation choices - and on the listener - the ways it focuses the perceived tonal contexts. Knowledge of how the sustain pedal is used to reinforce harmonies in music can also help improve systems for automated transcription.

We compare the MuSA.RT analysis of performances of Johann Sebastian Bach's Prelude No. 1 in C major from the *Well-Tempered Clavier*. The piece is chosen for its harmonic clarity and rhythmic simplicity for illustrative purposes. The first two bars of the Prelude are shown in Figure 1. Continuing the pattern laid out in the first two bars, the entire Prelude consists of a sequence of arpeggiated chords, providing clear indications of points of harmonic change. The pedal points, played by the left hand, clearly outline significant structural tones. Relatively straightforward pedaling strategies can be implemented for the piece.

Figure 1. Bach Prelude No. 1 (beginning)

We record and compare the MuSA.RT analysis for performances of the Prelude, with and without sustain pedal use. We provide summary statistics for the data in each scenario, and the inferences derived from the statistics. Our purpose is to show that judicious use of the sustain pedal in piano performances serves to clarify tonal structures.

II. THE SUSTAIN PEDAL

Modern pianos have two or three pedals. The rightmost pedal is the sustain pedal. When the sustain pedal is depressed, the dampers are lifted off all strings in the piano, allowing them to freely vibrate. By enabling sympathetic vibrations, the sustain pedal also has the effect of increasing the volume of the sounding tones. The sustain pedal can be applied to attain sound volume, in both chordal and scale passages; to attain legato effects that are impossible for fingers alone, such as sequences of harmonically similar or different chords; and, to achieve a variety of timbres (p.124-140, Gieseking & Leimer, 1972). The other standard pedal, usually the leftmost one in the set of three, is the una corda pedal, which softens the tone produced. The middle pedal is typically a sostenuto pedal, sustaining only the notes that are depressed when the pedal is activated.

Experts agree that pedal markings should be taken with a grain of salt, and adapted to each new situation, guided by the way one hears the harmonics of the sounding tones in each new space. Gyorgy Sandor emphasizes that

> "the manner, frequency, quantity, and intensity of pedal work must be guided primarily by the ear: constant listening, awareness, and control are needed to produce the desired sounds. Every piano is different, and acoustic conditions vary greatly … the only constant is the sound image we want to create …" (p.178, Sandor, 1995))

While pedaling on the piano is often executed with much care, different experts can pedal the same piano passage in quite diverse ways to great effect. Apart from the full and non-depression of the sustain pedal, there exists a gamut of possible ways to apply the sustain effect, ranging from partial pedal depression to continuous tremolo or vibrato (fluttering) effects.

Most pianists avoid making general statements about the use of the sustain pedal.

> According to Schnabel, who objected to "educational editions prescribing the pedal to be used in every bar once and for all", "there must be flexibility left to cope spontaneously with an unexpected acoustic situation, created by the hall, or the piano, or both. … Most pianists cannot say exactly how they used the 'instrumental' pedal, and, according to Schnabel, this is as it should be." (p.159, Wolff, 1979)

A few have ventured to lay down some guiding principles regarding the use of the sustain pedal. While they may disagree about the specific technique of pedaling, for example whether to use syncopated pedaling (pedaling after the onset) or on-time pedaling (pedaling with the note onset), all agree that the art of pedaling depends very much on one's hearing of the mixing of the harmonics.

In general, one can pedal note and chord sequences that are similar, and should clear the pedal when dissonances accumulate. Sandor, a proponent of pedal use "whenever it doesn't sound bad", and who advocates pedal use for arpeggios, runs, and tremolos in music of any period or style,

> "The art of pedaling hinges on our ability to blend harmonics. For example, just take one set of harmonics: by accentuating and coloring different harmonics within the same column [of sound], we create innumerable sound effects, even without varying the dynamics. … Since the right pedal helps to synchronize sounds, chords, and harmonies, a thorough knowledge of harmony is desirable for its effective manipulation." (p.167-170, Sandor, 1995)

III. VISUALIZING TONAL STRUCTURES

Our instrument for studying harmonic coherence in pedaled versus non-pedaled piano passages is the MuSA.RT interactive tonal analysis and visualization software. MuSA.RT shows the pitches played with their note names, the closest triad, and the nearest key, as music unfolds in a performance. A scientific visualization of these tonal structures is computed using, and represented on, the Spiral Array Model.

The Spiral Array Model consists of a set of nested helices, on which is represented a kind of tonal entity. Pitch classes are represented on the outermost helix (shown in silver / light gray in Figure 2). The major and minor triad representations are generated as weighted sums of their component pitch classes, and themselves outline two inner helices. Similarly, the major key and minor key helices are generated from their defining triads.

A tonal context is represented by a Center of Effect, (CE), a weighted sum of the recently sounding pitch classes. The weights on the pitch classes decay over time, according to a linear filter. Two context trackers, called Centers of Effect (CEs), show the short-term and long-term history of the tonal trajectories.

In MuSA.RT, the triangle outlining the pitch classes of the triad closest to the short-term CE lights up (in pink when it is a major triad, and light blue when it is a minor triad). This closest triad is found by a straightforward nearest neighbor search. The C major triad is closest to the short-term CE in Figure 2.

Similarly, the closest key representation is found by a nearest neighbor search; the key representation lights up as a red(major)/blue(minor) sphere with radius inversely proportional to the distance of the long-term CE to that key representation. The name of the closest key is further indicated by a dodecahedron around the its name.

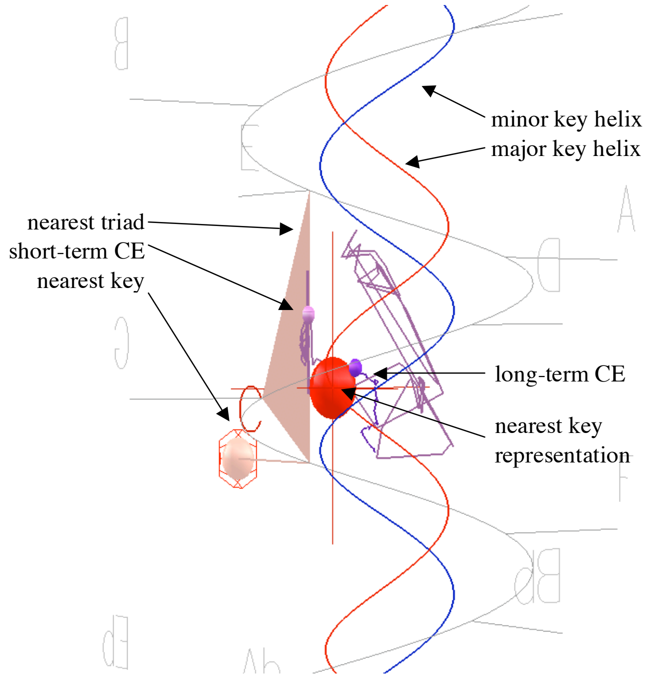

Figure 2. MuSA.RT screenshot

When in auto pilot mode, the three-dimensional model rotates dynamically so that the current triad representation moves to the far side, allowing one to better view the CE trails. When the auto pilot mode is off, a game pad control allows the user to navigate through the space to better view the tonal objects.

Earlier versions of MuSA.RT have been employed in the visual analysis of tonal patterns in Pachelbel's *Canon*, Bach's *Unaccompanied Cello Suite*, BWV 1007, and Barber's *Adagio*

(Chew & François, 2005), and in the visualization of musical humour in P. D. Q. Bach's *The Short-Tempered Clavier* (Chew & François, 2007).

The latest incarnation of MuSA.RT, Opus 2.7, possesses the capability of capturing pedal effects. When the sustain pedal is depressed, the pitch classes are still considered to be 'on', even when the physical key is released, and continue to contribute to the position of the CEs. When the sustain pedal is released, all pitches except those whose physical keys are depressed are switched 'off'.

A. Related Work

Several other researchers have proposed software tools for visualizing tonal structures. The research effort most similar in spirit to MuSA.RT is Petri Toiviainen's (2005) real-time tonal analysis and visualization software based on a short-term memory model and self-organizing maps (SOM). Like MuSA.RT, it allows one to examine the clarity and locus of tonality at any given time. While MuSA.RT presents a visualization based on the three-dimensional Spiral Array Model, the visualization in the SOM method is presented on a two-dimensional surface. In MuSA.RT, tonal entities such as pitches, chords, and keys, appear as geometric objects in the two dimensional space. The SOM method presents colors in flux on Carol Krumhansl's (1990) key space; red and hot color regions indicate tonal proximity, while blue and cool color regions point out distant tonal relations.

In his keyscapes, Craig Sapp examines the changing keys in a piece of music at multiple hierarchical levels, from the highest (comprising of an analysis of the entire piece) to the lowest (at each individual unit of time). The resulting multi-scale map is presented in two-dimensions, with each key indicated by a color code.

IV. EXPERIMENT DESIGN

Bach's Prelude from his *Well-Tempered Clavier* is the focus of our experiment. The beginning of the Prelude was shown in Figure 1, and the end (the final four bars) is given in Figure 2.

Figure 2. Bach Prelude No. 1 (end)

One of the authors (Chew) played the Prelude twice, once with pedal, and once without pedal, without visual feedback from the MuSA.RT software. To reduce the expressive variability to a minimum, both play-throughs of the Prelude were done to a metronome set to 64 bpm, which was deemed to be a comfortable speed by the pianist. The approximate pedaling strategy (for the pedaled play-through) is depicted in Figures 3 and 4. For the majority of the piece, a strategy like that shown in Figure 3 was employed.

Some variance in the pedaling was observed towards the end of the Prelude, particularly in the final three bars. The approximate pedaling applied is shown in Figure 4. The exact pedaling strategies recorded by MuSA.RT will be shown later.

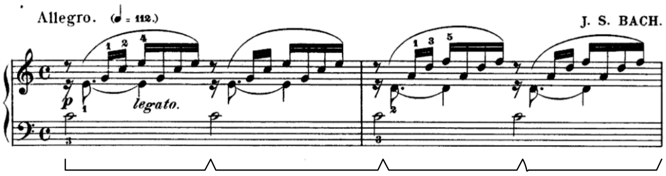

Figure 3. Bach Prelude No. 1 (beginning with pedal)

Figure 4. Bach Prelude No. 1 (end with pedal)

A. MuSA.RT Visualizations of the Performances

Figures 5, 6, and 7 show the screenshots (the front, left, and right views) from MuSA.RT after the first four bars of the Prelude, played with no pedal. Figures 8, 9, and 10 document the screenshots (the front, left, and right views) from MuSA.RT after the first four bars of the Prelude, played with pedal. Observe that the effect of the pedal smoothens both the long-term and short-term CE trajectories. The next section will study this observed effect quantitatively.

V. QUANTITATIVE ANALYSIS

For both the pedaled and non-pedaled performance of the Prelude, we first analyze the data separately, then compare the statistics.

A. Without Pedal

The data recorded at any given time t are:

t = the time stamp;
I = the indicator vector of pitch classes that are on;
p_{short} = the position of the short-term CE; and,
p_{long} = the position of the long-term CE.

The distance to all major and minor triads, C_M and C_m respectively, are computed, and the minimum distance recorded:

$$d_M(t) = \min \{ | p_{short}(t) - C_M |^2 \}$$
$$d_m(t) = \min \{ | p_{short}(t) - C_m |^2 \}$$

The distance to the closest triad is given by:

$$\min \{ d_M(t) , d_m(t) \}$$

Similarly, the distance to all major and minor keys, T_M and T_m respectively, are computed, and the minimum distance recorded:

$$D_M(t) = \min \{ | p_{long}(t) - T_M |^2 \}$$
$$D_m(t) = \min \{ | p_{long}(t) - T_m |^2 \}$$

The distance to the closest key is given by:

$$\min \{ D_M(t) , D_m(t) \}$$

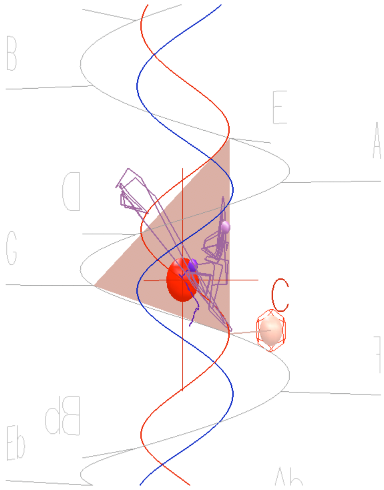

Figure 5. Bach Prelude No. 1 (first 4 bars) with no pedal (front view)

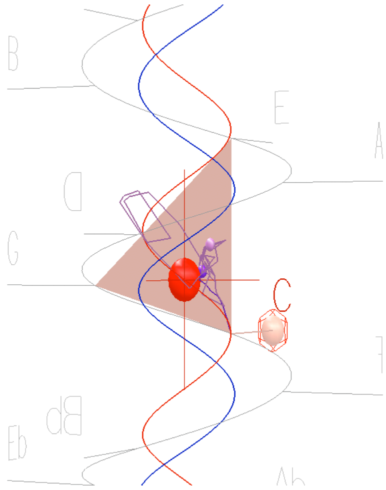

Figure 8. Bach Prelude No. 1 (first 4 bars) with pedal (front view)

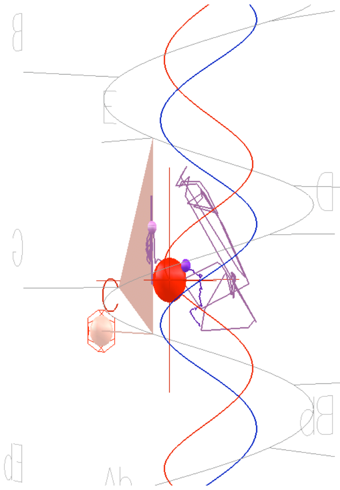

Figure 6. Bach Prelude No. 1 (first 4 bars) with no pedal (view from left)

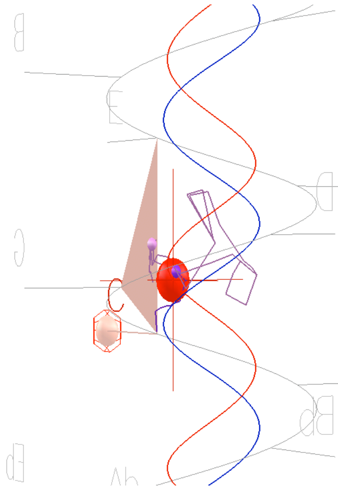

Figure 9. Bach Prelude No. 1 (first 4 bars) with pedal (view from left)

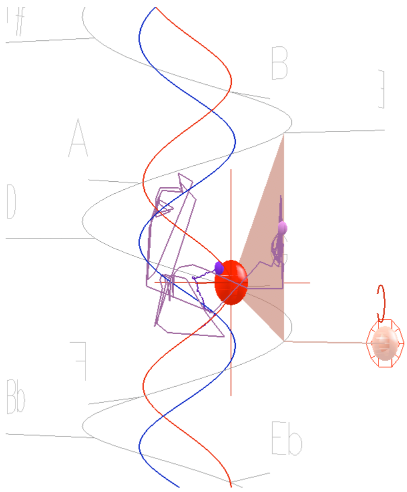

Figure 7. Bach Prelude No. 1 (first 4 bars) with no pedal (view from right)

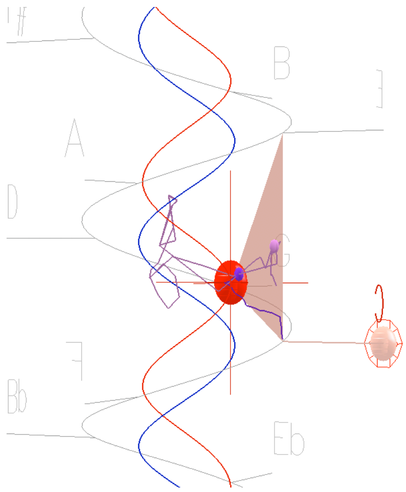

Figure 10. Bach Prelude No. 1 (first 4 bars) with pedal (view from right)

The following subsections will present and analyze these quantities for the two performances of Bach's Prelude, with and without pedal.

A. Analysis of Bach's Prelude Without Pedal

Figure 11 charts the minimum distance to major (red, bold line) and minor (blue, thinner line) triads for Bach's Prelude played without pedal. The x-axis shows the time in milliseconds. Figure 12 shows the histogram of the distances to the closest triad (the lower value between the two graphs in Figure 11). The average distance to the closest triad was 0.4053, with standard deviation 0.1471. The summary statistics are presented in Table 1.

Figure 13 charts the minimum distance to major (red, bold line) and minor (blue, thinner line) keys for Bach's Prelude played without pedal. Figure 14 shows the histogram of the distances to the closest key. The average minimum distance to key is 0.3245, with standard deviation 0.1313.

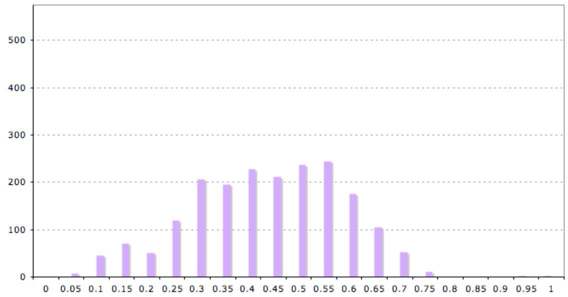

Figure 12. Bach no pedal minimum distance to triad histogram

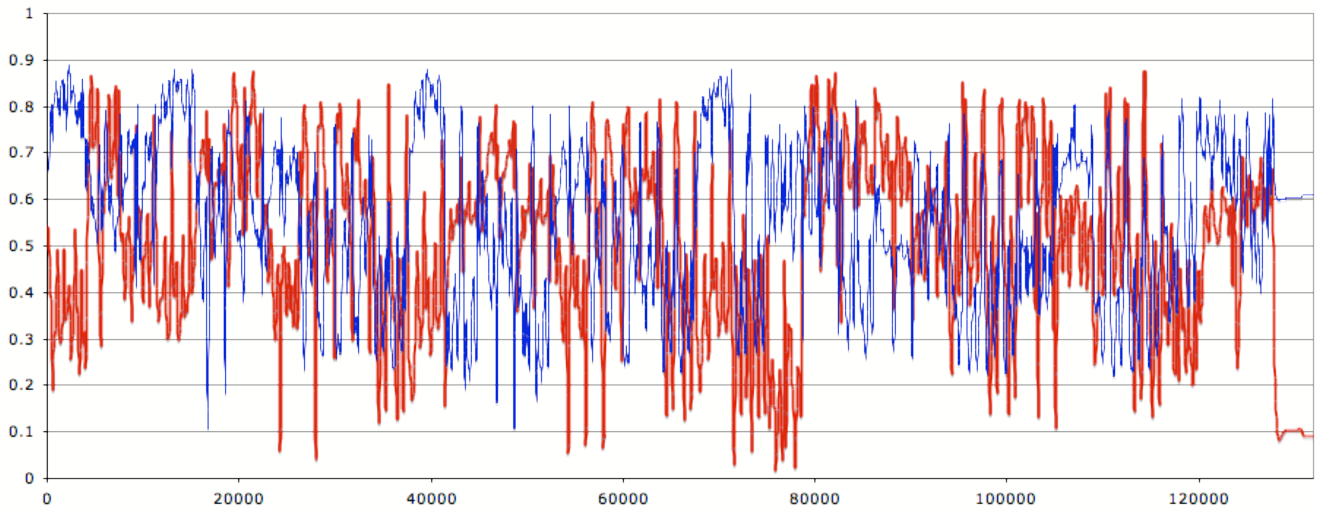

Figure 11. Minimum distance to major (red, bold) and minor (blue) triads for Bach's Prelude No. 1 (whole piece) with no pedal

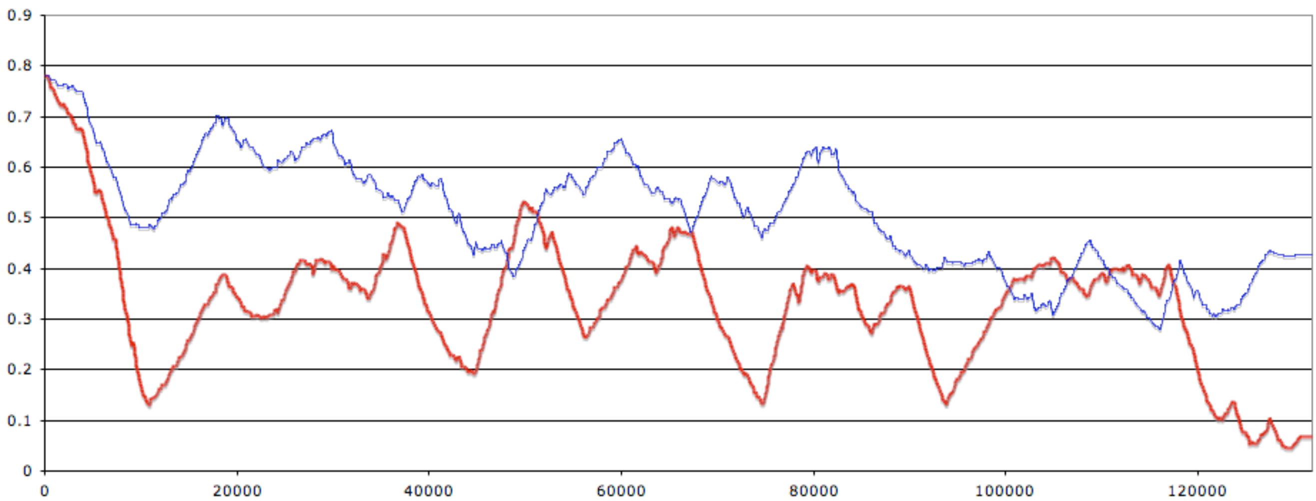

Figure 13. Minimum distance to major (red, bold) and minor (blue) keys for Bach's Prelude No. 1 (whole piece) with no pedal

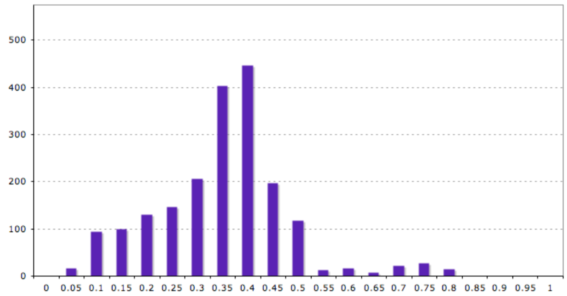

Figure 14. Bach no pedal minimum key distance histogram

B. Analysis of Bach's Prelude With Pedal

Figure 15 shows the distance to closest major (red, bold line) and minor (blue, thinner line) triad graphs for Bach's Prelude played with pedal, and Figure 16 shows the histogram of the distances to the closest triad. In Figure 15, a graph of the sustain pedal activation (on) and release (off) times appears near the x-axis. The average distance to the closest triad is 0.4034, with standard deviation 0.1427.

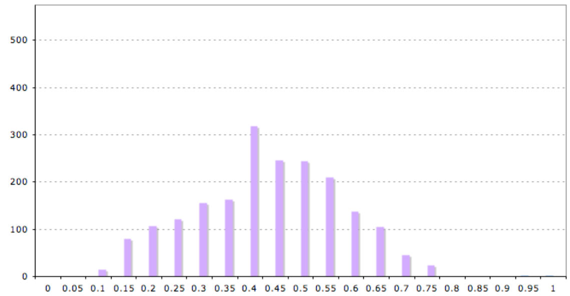

Figure 16. Bach with pedal minimum distance to triad histogram

Figures 17 and 18 show the corresponding plots for distance to major and minor keys. The average minimum distance to key is 0.3067, with standard deviation 0.0928.

C. Comparison of Data With and Without Pedal

Table 1 shows some of the summary statistics for the distance to closest triad and distance to closest key for the test data generated with pedal and without pedal.

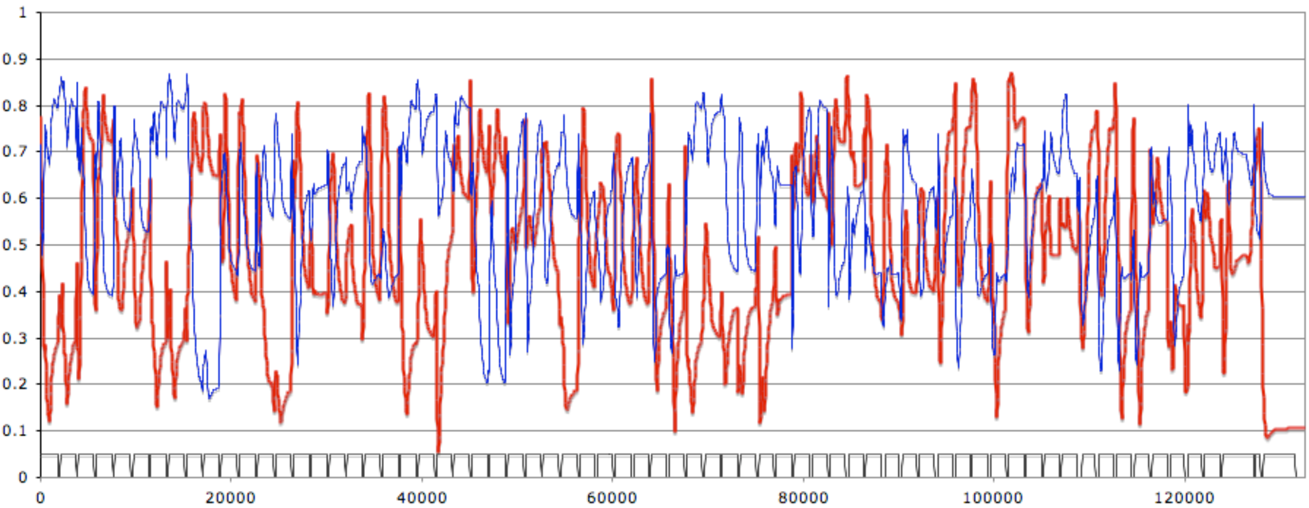

Figure 15. Minimum distance to major (red, bold) and minor (blue) triads for Bach's Prelude No. 1 (whole piece) with pedal

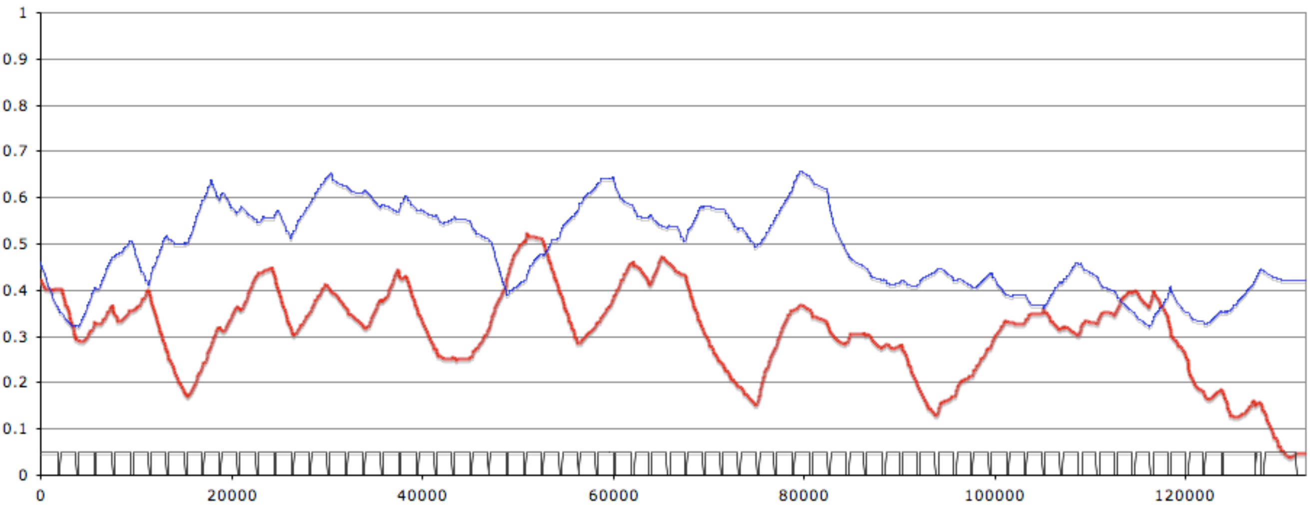

Figure 17. Minimum distance to major (red, bold) and minor (blue) keys for Bach's Prelude No. 1 (whole piece) with pedal

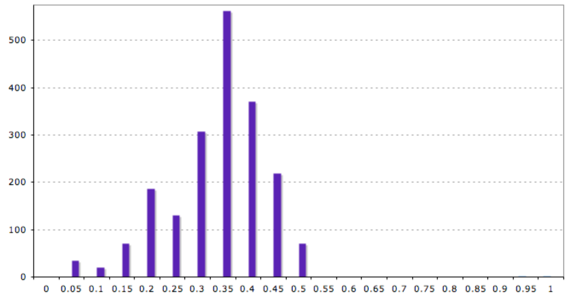

Figure 18. Bach with pedal minimum key distance histogram

Table 1. Comparisons of Summary Statistics.

	No Pedal	**With Pedal**
Minimum distance from short-term CE to triad		
Mean	0.4053	0.4034
Mode	0.0907	0.1054
Standard deviation	0.1471	0.1427
Minimum distance from long-term CE to key		
Average	0.3245	0.3067
Mode	0.0684	0.0462
Standard deviation	0.1313	0.0928

We conduct a difference of means test between the distance from the short-term CE to the closest triad, for the pedaled and non-pedaled performances. The t-statistic is 0.4021. With 3921 degrees of freedom, the critical value for a two-tailed test, with $\alpha = 0.05$, is 1.9606. The p-value is 0.6876. Thus, we cannot reject the null hypothesis that the means are equal.

We conduct a similar difference of means test between the distance from the long-term CE to nearest key, for the performances with and without pedal. The t-statistic is 4.9027. With 3529 degrees of freedom, the critical value for a two-tailed test, with $\alpha = 0.05$, is 1.9606. The p-value is $9.878\text{x}10^{-7}$. Thus, we can reject the null hypothesis that the means are equal.

While the t-test reveals a difference of means for the distance from long-term CE to nearest key, thus supporting the hypothesis that the pedaled performance of the Prelude results in more coherent key patterns, the t-test was not able to confirm whether the detected chord patterns are better structure in the pedaled version. The next test aims to show that while there may not be an obvious difference of means between the distance from short-term CE to nearest triad for the Prelude performance with and without pedal, the use of the sustain pedal does lead to smoother CE trajectories, as revealed by the minimum distance to triad/key values.

Table 2. Smoothness of Distance to closest entity.

	No Pedal	**With Pedal**
Distance from short-term CE to closest triad (x10^{-3})		
Mean Squared Differential	4.6888	1.4774
Distance from long-term CE to closest key (x10^{-5})		
Mean Squared Differential	1.2233	0.6591

We approximate the smoothness of the distance from short-term/long-term CE to closest triad/key graphs by taking the average of the distance change between adjacent points on the respective graphs. The resulting numbers are reported in Table 2, showing that the pedaled version does indeed result in smoother distance to nearest triad/key changes.

VI. CONCLUSION

We have presented a series of quantitative tests to measure the effect of the sustain pedal on the coherence of the projected tonal patterns as measured by the Spiral Array Model implemented in MuSA.RT. The results show that increased tonal coherence can be observed as closer average distance from long-term CE to nearest keys. While the average distance from short-term CE to nearest triad is not conclusively shortened by the effect of the sustain pedal, the distance from CE to nearest triad does change in a markedly smoother fashion, leading one to believe that at least chord transitions may be perceived to occur more smoothly in a pedaled performance.

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