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Understanding movement during performance: A recurrence quantization approach

Alexander Demos, Till Frank, and Roger Chaffin

Department of Psychology, University of Connecticut, USA

Traditional methods of signal analysis of one-dimensional data have limited use in unraveling how the movements of a musician in performance relate to the musical structure because performers' movements are complex. Methods developed for the analysis of multi-dimensional chaotic systems, such as recurrence quantification analysis, are well suited to dealing with complex data of this type. We compared traditional and non-traditional methods of signal analysis by applying them to the movements of a musician.

Keywords: movement; signal analysis; phase-space reconstruction; recurrence quantification analysis

Watching a musician move in performance can give the audience insight into the musical expression the performer is trying to convey (Davidson 2007). The movements of a musician may also provide visual information about other aspects of the music, such as its musical structure (Shove and Repp 1995). Traditional methods of exploring the complex movements of musicians in performance typically rely on video coding or point light recordings that often provide one-dimensional data (Davidson 1993, Davidson 2007). In addition, researchers have typically used analyses that assume data that meet the requirement of stationarity (i.e. the mean and variance do not change over time). However, movements in performance are neither stationary nor one-dimensional.

By using phase-space reconstruction (PSR), a technique from dynamical systems theory developed for analyzing chaotic systems, movements during performances can be completely reconstructed from information recorded in only one dimension (Takens 1981). Once the complete system has been reconstructed, it can be subjected to recurrence quantification analysis (RQA) to locate self-similarities within a performance. Further, cross-recurrence quantification analysis (CRQA) can compare different performances. RQA and CRQA provide visual and quantitative evidence of both the amount and location of recurrence in the movements as they unfold over the course of the performance.

We compared these non-traditional approaches (RQA and CRQA) to more traditional methods such as Fourier transformation (FT) and Hilbert phase transformation (HPT). We applied both traditional and non-traditional approaches to the movements of a violinist playing a Bach prelude in order to assess their ability to identify regularities in the violinist's movements.

METHOD

The movements of an amateur violinist (the first author) performing the Cello Suite No.1 (Prelude) by J.S. Bach ($^4/_4$ meter and 42 bars long) were recorded on a Nintendo wii Balance Board (at 35 Hz). We extracted data for side-to-side movements (x-axis) from the recordings of three successive performances using Matlab 2009, using the wiimote toolbox and the psychophysics toolbox (Brainard 1997). The three performances were roughly equal in length (135.38 s, 136.87 s, 135.58 s). The location of the beats in the music were extracted manually from an auditory recording of the performances. Figure 1 displays the movements as changes in postural sway in the x-direction for the first 30 seconds of the three performances.

RESULTS

Traditional methods

To explore the periodic components of the movements, the performance was divided into 21 sections, where each section included the movement from two non-overlapping measures. For each section, the average tempo (in Hz) was divided by the peak component frequency of the movement (extracted with FT). As can be seen in Figure 2, each performance contained movements that were roughly in simple ratios to the musical beat (2:1, 3:1, 4:1, and 8:1). However, there was little consistency across performances in which ratio occurred in each section of the music (Cronbach's α=0.60).

To more closely explore the periodic regularities, the phase of movement at each musical beat was determined, using HPT, and analyzed for phase-locking with a Rayleigh test. Phase-locking takes places when the periodic movement occurs at the same point in the cycle at each beat, indicating that the performer's movement is locked in a regular pattern with the beat. Except

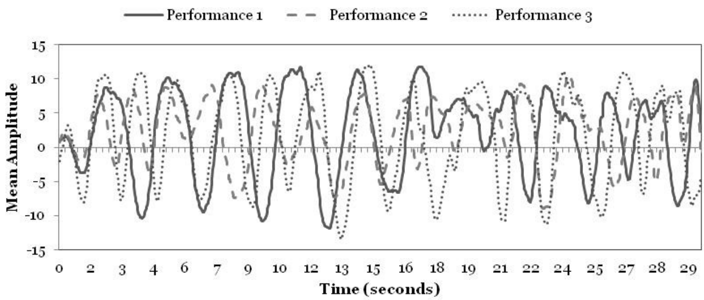

Figure 1. Movement of performer for the first 30 s of the three performances.

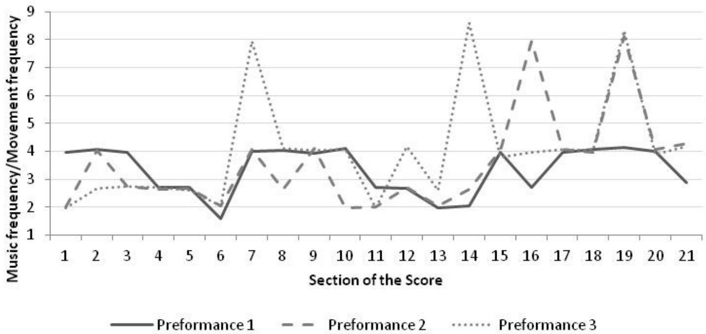

Figure 2. Ratio analysis using Fourier transformation.

for the first performance, there was no significant phase-locking between the music and performance. The presence of simple ratios between movement and musical beat in the FT analysis and the absence of phase-locking in the HPT analysis suggests that the relationship of movement to the musical beat was complex and possibly chaotic.

Using traditional methods, it is difficult to test for self-similarity within each performance. To do so requires searching for a particular movement pattern from one performance in the entire movement time-series, a time consuming process that requires the researcher to set many search parameters, such as the size of the pattern and the degree of similarity to search for.

As a first step, that did not require such complex methods, we evaluated the overall similarity of the performances by performing cross-correlations between the three performances. Since the performances were not exactly the same length, the data were trimmed to accommodate the shortest performance. The results suggested low to moderate levels of similarity between the performances (P1 vs. P2 r_{xcor}=0.45 at lag 1.4 s; P1 vs. P3 r_{xcor}=0.20 at lag 15.5 s, P2 vs. P3 r_{xcor}=0.28 at lag 0.4 s).

Summarizing the results of these traditional methods, the FT showed that the movements over the whole piece were regularly related to the beat; however, the HPT showed that movements often were not phase-locked with the beat. These methods, thus, identified some regularity in the movements. However, the absence of phase-locking suggested that the system might have been chaotic. The next section explores the same three performances using RQA, a method more appropriate for chaotic systems.

Non-traditional methods

To explore regularities and to test for self-similarity within each performance, an RQA was run on each performance. To prepare the data for RQA, each raw time-series was converted to z-scores. Next, a PSR (with a time-delay of 23 and embedding dimension of 4) was used to reconstruct the complete movement of the performance in high-dimensional space. The reconstructed performance was then submitted to RQA analysis (with a radius of 0.81 SD units). To evaluate the degree of structure in the resulting data, the movement from performance 1 was shuffled and plotted using the same parameters (see Figure 3).

Figure 3 shows plots of the time-series of the movement against the musical measures in which they occurred. The analysis compares each data point to itself (points on the diagonal) and to all the other points in the series. Each dot represents a place of recurrence, where the movements in high-dimension space "nearly" overlap. The diagonal line across the centre of the figure (line of identity) shows where the movements perfectly overlap—they are identical because they occur at same time. The shuffled plot contains the same number of recurrence points (dots) as the original performance but in random order. Comparison with the original performance shows that the movements were, in fact, highly structured.

As can be seen in Figure 3, movements in the first five measures repeat in each measure. This initial movement pattern is again repeated whenever the same musical pattern repeats, for example in bars 15-16 and 18-19. Overall, performance 1 showed recurrence in locations where music patterns recurred.

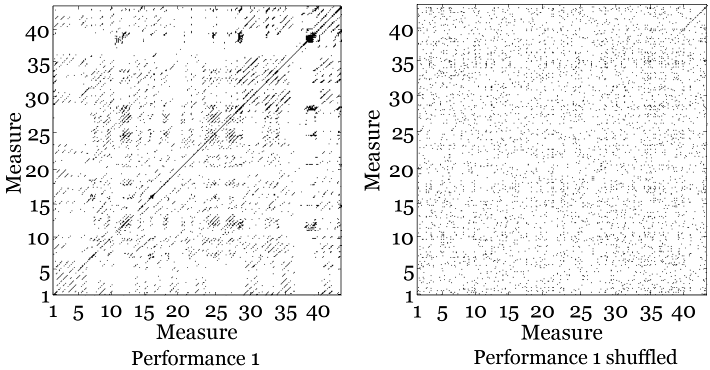

Figure 3. RQA plot of performance 1 vs. performance 1 shuffled.

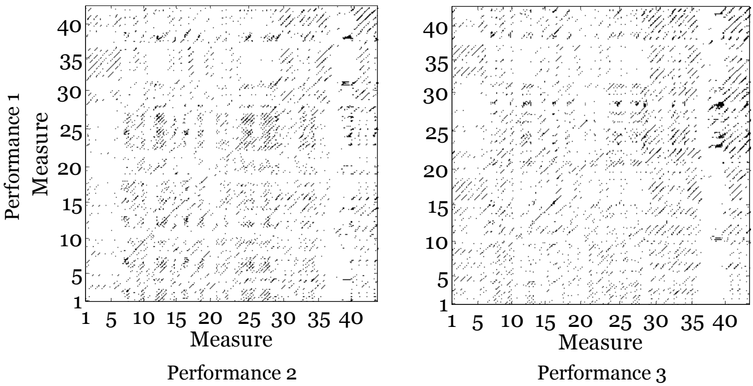

Figure 4. CRQA plot of performance 1 vs. 2 and 1 vs. 3.

Close comparison of the musical structure and the RQA plot reveals a wealth of such detailed relationships between the movements of the performer and the musical structure; the above description provides only a sample. In addition to the visual presentation, RQA and CRQA provide several quantitative measures not discussed here (for a review, see Marwan *et al.* 2007).

To measure similarities across the three performances, we performed CRQA between the performances, using the same parameters for each performance. The CRQA plots for performance 1 vs. 2 and 1 vs. 3 are shown in Figure 4.

As can be seen in Figure 4, there is partial line of identity for performance 1 and 2 indicating similarities in movement patterns between the two performances. For example in performance 1 vs. 2, there were high levels of recurrence starting at bar 24 and stopping at the end of the phrase (bar 29). However, the same pattern is not seen as clearly in performance 1 and 3.

DISCUSSION

Musicians and audiences alike believe that there is an intimate relationship between movement and music, but traditional methods have had difficulty in quantifying that relationship. Traditional methods can show how a performer's movements relate to the musical beat, but they are not well suited to showing more complex relationships, such as the recurrence of movements during performance. RQA and CRQA, in contrast, can reveal similarities between movements both within and across performances. The relationships between recurrence and musical structure that we have identified using these methods suggest that the intuition of an intimate and complex relationship between music and performers' movements is correct.

Address for correspondence

Alexander Demos, Department of Psychology, University of Connecticut, 406 Babbidge Road, U-1020, Storrs, Connecticut 06269, USA; *Email:* alexander.demos@uconn.edu

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