Analysis of Leadership in a String Quartet

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ABSTRACT

This paper addresses the study of leadership in string quartet starting from the analysis of non-verbal behavioral cues. It considers in particular the movement of musicians' head towards a common point of reference for the ensemble, called the *ear*, which corresponds to the subjective center of the string quartet. By applying a method based on Granger Causality we investigate whether and how each musician's distance is influenced by the other musicians. This approach aims at identifying the potential leader(s) by characterizing their greater capacity to influence others' behavior.

Categories and Subject Descriptors

H.5.5 [**Information Interfaces and Presentation**]: Sound and Music Computing

General Terms

Experimentation

Keywords

Leadership, Granger Causality, Music Ensemble

1. INTRODUCTION

An increasing number of recent studies has adopted music ensemble to study social interactions. State of the art research includes studies on interpersonal interaction in musician - musician [5, 8, 13], conductor - musicians [3, 15], and in musician - listener [7] scenarios. Several studies analyze the interaction among musicians of a string quartet (SQ) by using observations and interview methods. Others, including our approach, model interaction by means of quantitative measures.

Figure 1: A picture of the string quartet Quartetto di Cremona during a recording session at Casa Paganini, Genova. The subjective center of the quartet, the *ear* has been set up following the musicians' instructions. See, within the red rectangle, the motion capture marker above the tripod placed between musicians.

The SQ scenario stands as an original test-case to study a prominent aspect of social interactions, *leadership*. In a SQ, all musicians participate at an equal level to the performance and no preexisting hierarchy is set between them as it can be seen in an orchestra (director Vs musicians). SQ has for example been described as a Self-Managed Team, i.e., a working structure where all partners share an equal responsibility in the development of a project [6].

Our approach to study leadership in SQ consists of characterizing the interaction between musicians starting from their behavioral cues. In the present study we focused on the distance of the musicians' head with respect to the *ear* of the quartet. The *ear* refers to a subjective center, defined by the four musicians and located at nearly equal distance from each of them (see Figure 1). The *ear* is called such as it refers to a mental external listener that would gather the musical contributions of all the musicians. This center stands as a reference for all musicians during the performance and helps them to coordinate and reach a coherence sound ensemble. In this sense, the distance achieved from each musician' s head towards the *ear* may reflect how each musician stands with respect to the group over the performance. We aim at analyzing to what extent the variations of the musician's head distance with respect to the *ear* is conditioned by the other musicians' head distance. Under this perspective, Granger Causality can be used as a method to quantify the influence of the behavior of a performer (in terms of head distance) on the behavior of her quartet mates.

The paper is organized as follows: Section 2 gives a brief overview of the issues related to the analysis of social interaction in string quartet, and in particular about the analysis of leadership in such context; in Section 3 we detail the multimodal setup we developed for recording musicians' performance and the method we adopted to study the interactions within the ensemble; in Section 4 we present the results obtained through the application of the Granger Causality method; we conclude the paper in Section 5.

2. BACKGROUND

Research on social interactions in SQs has mainly focused on leadership through the observations of student and professional rehearsals [14, 6]. Gilboa et al. [6] showed for example that the regular presence of a leader may ensure group cohesion and facilitate the collaborative music-making process. However, leadership which generally refers to a person's capacity to guide people by means of his social and organizational skills [12], may uncover original forms within the SQ. The four musicians (first violin, second violin, viola and cello) of a SQ play specific roles, possibly dynamically changing, during a performance, and their individual behavior is usually strongly affected when playing altogether. King [14] identified team roles in music ensembles that characterize types of interactions between co-performers: *leader, deputy-leader, contributor, inquirer, fidget, joker, distractor* and *quiet one* [20]. These roles can be assumed alternatively by the different members of the ensemble over the various rehearsals but tend to remain constant for each rehearsal taken individually. Rather than a well delimited leader as exemplified by the director in an orchestra, the SQ case actually exhibits a variety of "leadership patterns" [6] that can occur at different levels: (i) *Social statute*: the first violin of a SQ has a tradition of leadership in western music [6]; (ii) *Musical structure*: the musician that is playing the main theme assumes the role of leader. The music score defines the music structure, e.g., the main themes, the accompaniment,thus defines the roles that the musicians must play in each moment of the performance; (iii) *Performance techniques of the ensemble*: the leader may assume a set of performance techniques to maintain the group cohesion (e.g., keeping in time or setting a particular musical phrasing).

In previous studies we studied leadership in SQs in terms of chronemic aspects (e.g., anticipation) [16] and in term of complexity of the non-verbal behavior (e.g., group regulation) [10]. In this paper we focus on a different component of leadership related to the causality of one behavior upon another.

3. METHOD AND SETUP

3.1 Head movement

The analysis presented in this paper concerns the time series data of the musicians' head distance to the *ear*. Head movement plays a central role in the non-verbal communication in general [9], and in music in particular [4, 10, 2]. Head and upper body sway include movements, which are separate from technical or functional movements (instrumental gesture). In this sense, head movement and upper body sway are apt to express the phrasing and "breathing" of the music interpretation without being submitted to the constraints observed for other limbs such as the hands to produce the sound itself. They form shapes, embodied expressions of the models of the high-level musical structures the musician is interpreting. Head movements can also be explicit, to indicate specific moments during the performance requiring synchronized start, and may convey emotional states to facilitate interpersonal coping.

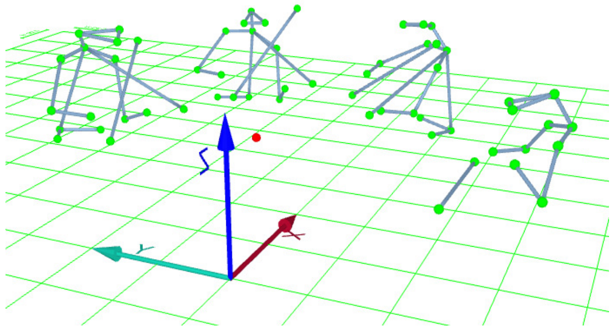

Figure 2: A Motion Capture (MoCap) representation of the four musicians of the Quartetto di Cremona SQ.The subjective center of the quartet, the *ear* is represented by a red dot.

We hypothesized that among all possible movement, the distance variations of the head towards the subjective center of the SQ, *the ear*, might be relevant to study leadership. The expressive intent of a musician may actually impact upon the ensemble provided that such behavior be addressed to the other performers. A musician may entrain the other performers' reactions by helping them to understand that what she is doing is overtly addressed to them. The area surrounding the *ear* of the SQ may define a common space between all musicians. By acting within this space, a musician emphasizes that her expressive movement should be considered carefully and should trigger adequate responses. In this perspective, we analyzed how the musicians' head distance from the ear vary with respect to one other over the ensemble performance. The position of each musician's head center of gravity (COG) was computed starting from the three markers placed on the musician's head, two on the front and one in the back (see Figure 2).

3.2 Granger Causality

A time series x is said to "Granger cause" a time series y, if the past values of x provide statistically significant information to predict the next value of y ([11]). The prediction is computed using (typically linear) Auto-Regressive (AR) models. Two AR models are required: an unrestricted AR model where the history of all time series is assumed to contribute to the prediction of the current value of a time series; and a restricted AR model where the time series whose causality value (on the other time series) is computed is excluded from the history. Given two time series x and y, the

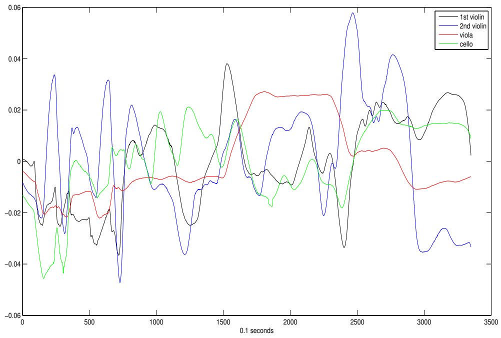

Figure 3: Time series of the distances between the head center of gravity of each musician and the *ear* of the quartet (Segment 1)

unrestricted model is defined as:

$$x(t) = \sum_{j=1}^{L} a_{U,j} x(t-j) + \sum_{j=1}^{L} b_{U,j} y(t-j) + \varepsilon_U(t)$$
$$y(t) = \sum_{j=1}^{L} c_{U,j} x(t-j) + \sum_{j=1}^{L} d_{U,j} x(t-j) + \eta_U(t) \quad (1)$$

where $x(t)$ ($y(t)$) is the value of the time series x (y) at time t, L is the length of the history observed in the model (i.e., the model order), $a_{U,j}, b_{U,j}, ...$ are the weights for the history (i.e., the model parameters), and $\varepsilon(t)$ and $\eta(t)$ are the residuals (prediction errors). The restricted model is defined as:

$$x(t) = \sum_{j=1}^{L} a_{R,j} x(t-j) + \varepsilon_R(t)$$
$$y(t) = \sum_{j=1}^{L} d_{R,j} x(t-j) + \eta_R(t) \quad (2)$$

The magnitude of the causality from x to y and from y to x are measured respectively as:

$$F_{x \to y} = ln \frac{var(\eta_R)}{var(\eta_U)}, \; F_{y \to x} = ln \frac{var(\varepsilon_R)}{var(\varepsilon_U)} \quad (3)$$

where var stands for variance.

To handle cases with more than two variables we can use Conditional G-causality ([**?**]). Suppose we have a third variable z and we want to compute $F_{x \to y|z}$ (i.e., the G-causality from x to y given z). In that case the unrestricted model takes into account all the three variables, while the restricted model for (y) is obtained by removing x only.

3.3 G-causality based analysis of leadership distribution

Similarly to [3], we carried out two types of analysis based on G-causality.

The first analysis aimed at evaluating the distribution of leadership within the quartet. We first segmented the time series of interest into observation windows and then computed the driving force (DF_{ij}) of each musician M_i on each musician M_j (with $i \neq j$) as:

$$DF_{i \to j} = \frac{\sum_{k=1}^{N_w} S(F_{M_{k,i} \to M_{k,j}}) - S(F_{M_{k,j} \to M_{k,i}})}{N_w} \quad (4)$$

where $M_{k,i}$ is the slice of time series M_i at window k, N_w is the overall number of windows and

$$S(F_{x \to y}) = \begin{cases} F_{x \to y} & \text{if } F_{x \to y} \text{ is statistically significant} \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

Given equations 1 and 2 the statistical significance of $F_{x \to y}$ is tested by running an F-test of the null hypothesis that all $c_{U,j}$ are null.

Each time series was segmented into 3-second windows sampled every second.

F was computed using pairwise G-causality, rather than conditional G-causality, as we did not want to miss an actual causal relation that may not be captured, or at least not entirely captured, if conditional G-causality were used instead. Suppose we have a time series x that influences two time series y and z, whose behavior is very similar and almost entirely dependent on x. By using conditional G-causality, $F_{x \to y|z}$ could be not significant since most of the behavior of z can be predicted looking at the history of y. Of course by using pairwise G-causality we can infer erroneous causal relations (e.g., in the example above, a significant $F_{z \to y}$) but, by taking into account both direct and "indirect" causal relations, we should guarantee that the actual leader time series is the one that has the highest number of significant and positive F.

To compute the leadership distribution we first computed the driving force (equation 4) of each musician on each other musician, for each segment, and averaged it over the segment repetitions. We then summed all the driving forces of each musician ($\sum_{j \neq i} DF_{i \to j}$) and sorted the four summed driving forces in ascending order. Finally, we fit the four data points with a second order polynomial (see figure 4). Considering the polynomial in descending power, the first two coefficients give us information about the distribution of the leadership. For example, (i) if both coefficients are very small (i.e., the polynomial is a straight line parallel to the x axis) the leadership will be equally distributed within the quartet, (ii) if the first coefficient has a large positive value (i.e., the polynomial is a concave curve), the leadership is concentrated on one single musician (see Figure 4, top), (iii) whereas if it has a large negative value (i.e., the polynomial is a convex curve) the leadership will be shared by more than one musician (see Figure 4, bottom).

3.4 G-causality based inter-musician communication

The second kind of analysis aimed at computing the degree of inter-musician communication, meant as the overall conditional G-causality within quartet. This overall conditional G-causality (where the G-causality between two musicians is conditioned on the other two) can be seen as the the overall amount of "active" (i.e., which affected the behavior of the musicians) information transferred from musician to musician. In this case conditional G-causality was used to count each fragment of information transferred only once.

The inter-musician communication was computed for each segment as the sum of significant conditional G-causality

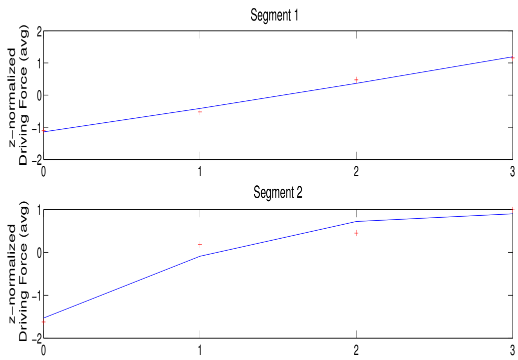

Figure 4: Leadership distribution in Segment 1 (top) and Segment 2 (bottom). The red crosses represent the actual average $\sum_{j \neq i} DF_{i \to j}$ of each musician i (numbered from 0 to 3). The solid line is the 2-nd order polynomial fitting of leadership distribution values. Note that the number associated to a musician in two different segments can be different.

Figure 5: The multimodal setup for the experiment at Casa Paganini - InfoMus: (a) motion capture, (b) frontal videocamera, (c) videocamera for individual violinist, (d) environmental microphones. Each musician wear markers for motion capture and EMG on the right arm. Piezoelectric microphones are in the body of the violin for individual measurements.

($\sum_{i,j \neq i} S(F_{i \to j|Q-\{i,j\}})$, where Q is the set of four time series, averaged over the segment repetitions.

3.5 Setup, Protocol and Stimuli

Setup. The experiment took place in a 250-seat auditorium, an environment similar to a concert hall, suitable for experiments in ecological setups. A multimodal recording platform has been setup to capture and analyze the movement, audio, and physiological data of the SQ musicians (see Figure 5). Musicians' behavior was captured by means of the Qualisys Motion Capture system (`www.qualisys.com`). Figure 2 shows the 3D points corresponding to the 16 markers placed on the musicians' joints and the 3 markers placed on the instrument. Original real-time applications based on the EyesWeb XMI software platform [1] have been developed to synchronize the Qualisys MoCap data together with video and audio data. Samples can be seen in the media section of the EU ICT FET SIEMPRE web pages (`www.siempre.infomus.org`). Before being analyzed, the MoCap data have been linearly interpolated and transformed in z-scores.

Protocol. The four professional musicians of the Quartetto di Cremona SQ were asked to play 5 times altogether the same 2 minutes length music segment without any break. They were instructed to play at best in a concert like situation The quality of each performance was assessed by musicians through post-performance ratings (e.g., level of satisfaction, expressivity, group cohesion).

Stimuli. The music piece performed by the SQ during the experiment was extracted from the Allegro of the String Quartet No 14 in D minor, known as Death and the Maiden, by F. Schubert. This piece is a staple of the quartet's repertoire and has been further divided into 5 musical segments, each characterized by a prevalence of a specific musical structure that set specific roles among musicians (see Section 2).

4. RESULTS

The results of the analysis of leadership distribution (LD) and of inter-musician communication (MC) are shown in table 1. Additionally we also wanted to find out the musicians

Table 1: Results of the analysis of leadership distribution (LD) and of inter-musician communication (MC). 1st and 2nd coeff. are the first and second coefficient respectively of the polynomial that fits the driving force values of the four musicians (ordered in ascending order from left to right, see figure 4)

	Leadership distribution 1-st coeff.	Leadership distribution 2nd coeff.	Inter-musician communication
Segment 1	0.02	0.7	0.52
Segment 2	-0.31	1.75	0.13
Segment 3	-0.18	1.07	0.26
Segment 4	-0.29	1.78	0.37
Segment 5	0.49	-0.55	0.28

who exerted more driving force by simply counting the number of time each musician exerted a positive driving force. Considering that, at each segment, the maximum number of positive driving forces of each musician is 3, the first violin turned out to exert the highest number of positive driving forces (10) followed by the second violin and the cello (7) and the viola (6). Three main findings can be considered.

The total number of positive driving forces computed for each musician gives a synoptic view on the relative importance of each musician in this SQ. On one side, it appears that the first violin stands out as a relative leader of the ensemble. It confirms in a quantitative way a role which is clearly recognized by all the musicians. On the other side, the other musicians (second violin, cello and viola) exhibit a total number of driving force values which remains close one with the other and not so different from the first violin. This restricted range of values may confirm that the SQ remains a remarkable example of egalitarian music ensemble where each participant has an active role

When considering the leadership distribution for each of the five segments, one can have a better understanding of how leadership is distributed. Specifically, two types of *lead-*

ership pattern [6] seem to emerge: (i) *Unipolar*, where one musician assumes exclusively the leadership and the others follow; (ii) *Bipolar*, where two musicians lead, constituting a leading subgroup within the ensemble. This distribution partially reflects the music structure. According to values in Table 1 and Figure 4 the performances relative to segment 1 (shown in Figure 4 and in Table 1) would fall into the first type of leadership pattern, Unipolar. Segment 1 is actually characterized by a homorhythmic texture where musicians tend to play at unison but over which the first violin emerges In Segment 5, first violin still leads the ensemble with particular dialogues with second violin. The other music Segments, 2 (shown in Figure 4), 3 and 4 fall into the second type leadership pattern, *Bipolar*. In Segment 2, the ensemble could actually be considered to be divided into two duets. In Segment 3 however, first violin dominates the ensemble, playing the melody alone, and accompanied by repetitive chords and tremolos of the other musicians. In Segment 4, a fugato writing style sets all musicians at the same level by replicating the musical subject over the different instruments; all parts should be equal with no leading part.

The analysis of leadership distribution based on the granger causality method may not reflect stricly the music structure even if for some segments, there is higher matching [15]. The analysis seems to model additional features which cannot be reduced to the music score itself, but may relate to the behavioral strategies devised by musicians to interpret altogether the music structure.

The information given by inter-musician communication (MC) is complementary to the one given by leadership distribution (LD). On one side, we know whether leadership is concentrated on a single musician or whether it is spread out over the different musicians, depending partially on the music structure. On the other side, the MC related results indicate the extent to which communication is achieved between musicians (i.e., amount of information transferred from musician to musician, see Section 3). With this index, one may assess whether a specific leadership pattern may facilitate the communication process within the ensemble. As shown in table 1 and illustrated in figure 4, a *Unipolar* leadership pattern (e.g., Segment 1) appears to pull the communication between musicians in a positive way (i.e. there is a high and continuous flow of information between musicians). Other examples (Segment 2 and 4) conversely show that a similar leadership pattern may result in different values of MC. In that sense, the inter-musician communication measures give an additional information about the effective success of leadership strategy that do not merely depend on the music structure itself but relates to how such pattern is effectively integrated by musicians during their performance.

5. CONCLUSION

This study considered the test-case of a SQ to understand how leadership can emerge in a group where all participants stands theoretically as equal. The analysis started from the computation of a non-verbal communication cue, the head distance towards the subjective center of the SQ called the *ear*. A method based on Granger Causality was applied to investigate whether and how each musician's distance is influenced by the other musicians. This approach identified the leader(s) by characterizing their greater capacity to influence others' behavior. Three main findings were considered. First, the total number of positive driving forces has given an overview of each musician roles among the ensemble revealing the relative prominence of the first violin. Second, the analysis of the the distribution of driving forces among the four musicians further characterized two leadership patterns: *Unipolar* Vs *Bipolar*. To the best of our knowledge, this is a first attempt to quantify what has been theoretically suggested in literature [6] Third, the inter-musician communication (MC) measures have assessed the impact of leadership patterns on the communication within the ensemble.

Future work includes the following directions: (i) computing a set of non-verbal expressive cues to characterize individual performance characteristics (e.g., entropy) and hence giving an insight on why some musician succeed in causing other's behavior; (ii) applying our approach on other modalities such as audio (e.g., loudness variations from one musician to the other).

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