Neuropsychologia 55 (2014) 98–104

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

Sensorimotor communication in professional quartets

Leonardo Badino[a,1], Alessandro D'Ausilio[a,1], Donald Glowinski[b,d], Antonio Camurri[b,1], Luciano Fadiga[a,c,*,1]

[a] RBCS – Robotics, Brain and Cognitive Sciences Department, IIT – Istituto Italiano di Tecnologia, via Morego 30, 16163 Genoa, Italy
[b] DIBRIS Department, University of Genoa, Genoa, Italy
[c] Section of Human Physiology, University of Ferrara, Ferrara, Italy
[d] NEAD-CISA, University of Geneva, Switzerland

ARTICLE INFO

Available online 10 December 2013

Keywords:
Music
Quartets
Joint action
Kinematics
Granger
Sensorimotor
Communication
Causality
Information flow
Mirror neurons
Motor control
Social interaction
Social neuroscience
Leadership

ABSTRACT

Non-verbal group dynamics are often opaque to a formal quantitative analysis of communication flow. In this context, ensemble musicians can be a reliable model of expert group coordination. In fact, bodily motion is a critical component of inter-musician coordination and thus could be used as a valuable index of sensorimotor communication. Here we measured head movement kinematics of an expert quartet of musicians and, by applying Granger Causality analysis, we numerically described the causality patterns between participants. We found a clear positive relationship between the amount of communication and complexity of the score segment. Furthermore, we also applied temporal and dynamical changes to the musical score, known by the first violin only. The perturbations were devised in order to force unidirectional communication between the leader of the quartet and the other participants. Results show that in these situations, unidirectional influence from the leader decreased, thus implying that effective leadership may require prior sharing of information between participants. In conclusion, we could measure the amount of information flow and sensorimotor group dynamics suggesting that the fabric of leadership is not built upon exclusive information knowledge but rather on sharing it.

1. Introduction

Other's action understanding requires a great deal of cognitive processing and efforts. Contextual information and prior knowledge are necessary and often enough to build reliable inferences about other's intentions (Brass, Schmitt, Spengler, & Gergely, 2007). However, another source of critical information is the other's movement kinematics (Rizzolatti & Sinigaglia, 2010). Actions have sensory effects. We use the sensory effects for motor control purposes and for information signaling to other individuals. Sensory effects of our actions are the only way another individual can "read" our intentions. The sender though, uses its motor system to encode such sensory messages. In this context, the mirror-matching hypothesis suggests that we use our motor knowledge as a template to match others' actions. In this manner, we might use our motor internal models to gain access to low-level control parameters implemented by the people interacting with us. Therefore, action understanding may benefit from the ability to model others' behavior implementation and use it as an additional prior, in a Bayesian perspective (Friston, Mattout, & Kilner, 2011).

The importance of this source of information, to the general action understanding, may be subject to data availability (full body vision vs. occluded vision), context richness (known vs. novel context) or expertise in a given task (Rizzolatti & Sinigaglia, 2010). If on one hand it is clear that, in general, partly occluded vision or the presence of a reliable context reduces the impact of low level decoding of others' action kinematics, on the other hand the case of experts may offer a different and interesting perspective. In fact, sport, dance or music experts do not obtain a simple rough interpretation of others' intentions as a general gist of their motivations. Rather, expertise in these activities is all about modeling with extreme accuracy low-level features and timing of actions (Aglioti, Cesari, Romani, & Urgesi, 2008). In fact, professional musicians, for instance, undergo important plastic changes induced by extensive motor and sensory training (Elbert, Pantev, Wienbruch, Rockstroh, & Taub, 1995; Schlaug, Jäncke, Huang, & Steinmetz, 1995; Pantev et al., 1998; D'Ausilio, Altenmüller, Olivetti Belardinelli, & Lotze, 2006). These anatomo-functional changes are also paralleled by enhanced ability to discriminate subtle changes in others' performance via predictive action simulation (Knoblich & Flach, 2001; Wilson & Knoblich, 2005; D'Ausilio, Brunetti, Delogu, Santonico, and Belardinelli (2010); Candidi, Sacheli, Mega, & Aglioti, in press).

* Corresponding author at: RBCS – Robotics, Brain and Cognitive Sciences Department, IIT – Istituto Italiano di Tecnologia, via Morego 30, 16163 Genoa, Italy. Tel.: +39 010 7178467; fax: +39 010 7170817.

[1] These authors equally contributed to this work.

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http://dx.doi.org/10.1016/j.neuropsychologia.2013.11.012

One facet of real expertise may be the refinement of sensori-motor skills as well as the domain-specific tuning of low-level sensori-motor feature extraction from others's behavior. In this vein, musicians have been extensively used with these purposes. For example, drummers have been used to study time processing (Cicchini, Arrighi, Cecchetti, Giusti, & Burr, 2012), violinist players for somatosensory plasticity (Elbert et al., 1995), piano players for sensori-motor integration (D'Ausilio, Altenmüller, Olivetti Belardinelli, & Lotze, 2006) or jazz players for creativity and improvisation (Limb & Braun, 2008). In sum, musicians proved to be extremely useful to study expertise in a diverse range of domains (Münte, Altenmüller, & Jäncke, 2002; Zatorre, Chen, & Penhune, 2007; Fadiga, Craighero, & D'Ausilio, 2009).

Ensemble musicians are indeed, a perfect model for sensori-motor decoding of others' behavior. As a matter of facts, professional ensemble musicians need to be talented instrumentalists as well as skilled in coordinating with the others. Therefore, these musicians are also a perfect model of expert social interaction and communication. For example, each violin section of an orchestra plays a score, which is often shaped in the form of a dialogue with the other violinists or the rest of the orchestra. Our previous investigation specifically focused on the communication dynamics between orchestra conductors and the musicians. The emergence of leadership was derived from the pattern of interactions evidenced by applying Granger Causality analysis to movement kinematics data (D'Ausilio et al., 2012).

In the present study we instead focused on professional quartets, since they offer a radically different scenario where leadership is not formalized and is shared between the musicians (but can still be identified and quantified as, e.g., in Varni, Volpe, & Camurri, 2010). Expertise in quartets actually translates more into the degree of coordination than the technical ability of a single player. Finally, quartets communicate using the same "language" whereas conductors use a different gestural and often very personal code to direct musicians. Therefore we might consider orchestras as a perfect model for unbalanced sensorimotor communication to study leadership behaviors, whereas quartets are an instance of socially balanced communication.

In the present study we measured head movements kinematics in a world famous quartet, playing a musical excerpt. We applied Granger Causality analysis to their head movement kinematics. Our analyses extracted two parameters, the Inter-Musician Communication (IMC) and the Musician Driving Force (MDF). Both parameters were also used in our previous investigations (D'Ausilio et al., 2012). These parameters reflect respectively the global amount of information flow in the group and the global impact each musician has in shaping the behavior of the other musicians. In addition to that we also selected those score segments that, from a musicological point of view, are more technically challenging for musicians' coordination. We predict stronger IMC during those complex segments to cope with the communication increase needed to coordinate the group. We also expect MDF to be stable across repetitions and to reflect the generally accepted hierarchy in quartets, designing the first violin as the leader among peers.

IMC and MDF were calculated in a normal and in a perturbed condition. Perturbation consisted in the application of dynamical (e.g., decrescendo) and rhythmic (e.g., accelerando) changes to the score, known by the first violin only. The other three musicians were blind to the kind of changes and to when they would happen. The rationale is that we altered communication between one musician and the others in specific moments in time. In this manner we can directly test if the perturbation in the amount and quality of communication is detected by our method. More interestingly however, we will be able to verify whether the leader of the group (first violin) increases or decrease his driving force in the perturbed scenario. In fact, in the normal scenario all musicians share the same amount of information about future events, whereas in the perturbed situation there is some relevant information for the group dynamics, which are possessed only by the leader. Therefore, if MDF from the first violin increases, leadership might be associated to the amount of exclusive information possessed by the leader, whereas if MDF decreases leadership can be conceived as the ability to drive a group, given a common shared ground.

2. Material and methods

2.1. Subjects

The experimental subjects were the four members of a professional quartet including a first violin, a second violin, a viola and a cello. The "Quartetto di Cremona" is an internationally recognized string quartet, which has already collaborated in previous experiments with authors AC and DG. The musicians were able to tolerate disturbance created by the multimodal setup (videocameras, markers, and on-body sensors) thanks to their previous experiences as test-subjects in similar experiments and longstanding experience of live performance in a variety of environmental situations (concert hall, television and radio broadcastings), and from their longstanding experience in music studio recordings, which are characterized by perturbing conditions very similar to the perturbing conditions occurring in scientific experiments like the one here considered. They complied very well with the experimenter demands. The study was approved by the SIEMPRE Project Management Committee and adhered to the standards laid down in the Declaration of Helsinki. All participants gave written informed consent before participating. The synchronized multimodal recordings of the musicians obtained for this experiment as well as the details of the SIEMPRE platform for multimodal recordings are made available to the research community from the EU ICT FET SIEMPRE web pages (http://www.siempre.infomus.org).

2.2. Stimuli

The quartet had to play some pieces of music selected from their repertoire so that their performance could already be at plateau and thus showing no learning during the experiment. The music piece 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 quartets repertoire since it gathers a number of very contrasted musical elements. The piece was selected for the variety of styles included. In fact, the piece contains homorhythmic structures where musicians tend to play at unison, fugato style which replicates the musical theme over the different instruments as well as concerto style melodic development interpreted by the first violin and accompanied by repetitive chords and tremolos of the other musicians. Each musical fragment lasted about 2 min.

Two expert musicians ran a score analyses in order to separate segments with high or low technical complexity. This segmentation was necessary for the subsequent data analyses. Technical complexity was defined according to rhythmic, dynamic or articulation characteristics. More specifically, rhythmic complexity was defined as changes that must result in perfect synchronization between musicians, e.g., homorythmic attack, or 'rallentando' at the end of a musical phrase. Dynamic complexity was defined as variations of intensity (nuance). Complexity in articulation was defined as changes of bow gestures, e.g., legato coming right after a staccato sequence. Generally speaking, complex segments were those sections offering some increased need to coordinate action between musicians.

2.3. Recording protocols

Two sessions of recordings (July, 13th and 14th 2011) were carried out following two different experimental protocols. In the first protocol (1st day), the four musicians were instructed to play 5 times the Schubert music piece at their best, in a concert like situation. In the second protocol (2nd day) the first violin, together with the experimenters, devised two "alternative" interpretations of the music score. These new versions maintained the exact same sequence of musical notes while including some modifications to the rhythmic and dynamic markings of the piece (e.g., playing forte where the written nuance is piano, speeding up when a 'rallentando' is requested. See Supplementary Figs. 1 and 2 for the modified scores). The other members of the quartet were not aware of these new versions before playing. Musicians played these new versions 5 times in total (version 1: repetitions 1, 3 and 5; Version 2: repetitions 2 and 4). Each session lasted 4 h.

2.4. Apparatus and set-up

The experiment took place in a 250-seat auditorium, an environment similar to a concert hall, suitable for experiments in ecological scenarios (see Fig. 1a).

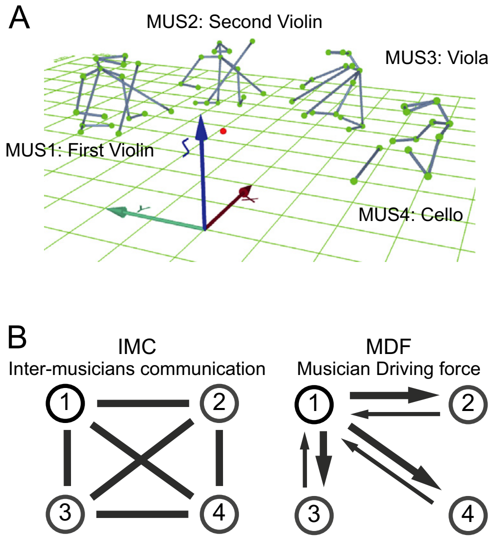

Fig. 1. Data and methods. Panel A shows the multimodal setup for the experiment at Casa Paganini – InfoMus. A stick-figure representation of the four musicians of the Quartetto di Cremona. The subjective center of the quartet, the Ear is represented by a red dot. In panel B the graphical depiction of the two types of Causality-derived measures extracted from kinematic data. The first one – Inter Musicians Communication – measures the global amount of communication among all players. The second – Musician Directed Force – is computed for each musician and correspond to how much he directed other musician more than he was directed by others (in the figure is represented the MDF from only one musician).

A multimodal recording platform was set up to capture and analyze the movement, audio, and physiological data of the musicians. Musicians' behavior was captured by means of the Qualisys Motion Capture system (Qualisys, Gothenburg, Sweden). For each musician, 16 reflective markers were placed on the musician body and 3 other markers were located on his instrument. In the present study we used only the three markers placed on the head. Two markers were placed on the musician forehead and one on the back of the inion. Data were recorded with the Qualisys Track Manager software. Furthermore, a real-time application based on the EyesWeb XMI software platform (Camurri, Coletta, Varni, & Ghisio, 2007) was developed to synchronize the 7-cameras Qualisys MoCap data together with video and audio recordings.

2.5. Measures and data pre-processing

The present study focuses on the time series data of the musicians' head distance to the subjective center of the quartet, called the Ear. Head movement is known to play a central role in non-verbal communication in general (e.g., Glowinski et al., 2010) and in music in particular (e.g., Castellano, Villalba, & Camurri, 2007, Davidson, 2005, Camurri, Volpe, De Poli, & Leman, 2005). Movements may be explicit markers, to indicate specific moments during the performance requiring synchronized start. Head movements may express the way musicians understand the phrasing and breathing of the music, and so provide information about the high-level emotional structures in terms of which the players are interpreting the music (Dahl et al., 2009). We were interested on group level interaction between musicians. In setting this goal we had to define a type of movement (or feature) which was devoid of any direct musical score implication unlike right arm bow control or left hand fingering. In fact, head movement has no direct connection to single note-level aspects of the score but rather reflects the group-level attunement around a general co-ordination goal. Furthermore, according to musicians' reports, the Ear refers to an imaginary point in space where musicians perceive music is coming from, when playing together. This point is located at nearly equal distances from each of them (see Fig. 1a). The area surrounding the Ear of the quartet stands as a reference for all musicians during the performance and helps them to coordinate and reach a coherent sound ensemble. We formulated the hypothesis that musicians' movements, relative to that virtual point, would have a particular significance for group co-ordination. In fact, if we consider music coordinated playing as an instance of complex multi-agent motor control, the group-level goal state should reside in the Ear of the quartet. Therefore, our choices were motivated by the fact we wanted to measure musicians' 'supra-segmental' interaction rather than low-level motor synchronization. On that basis, we analyzed how the musician's head distance with respect to the Ear varies over the ensemble performance.

We first defined musicians' position on stage and after few minutes of warm up, the location of the Ear was set before each recording session started. We asked the musicians to place a tripod with a reflective marker on top, exactly where they thought the Ear was for that session.

The position of each musician's head center of gravity (COG) was computed starting from the three markers placed on their musicians. Before being analyzed, the MoCap data had been linearly interpolated using the Qualisys Track Manager software standard functions. Euclidean distances between the head COG and the Ear were then computed for each frame. Data was acquired at 100 Hz.

2.6. Granger Causality analysis

We extract two parameters from the data, the Inter-Musician Communication (ICM) and the Musician Driving Force (MDF). Our definitions of ICM and MDF (See Fig. 1b) are both based on the concept of Granger Causality (G-causality). G-causality is a statistical concept of causality that is based on prediction. 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 (Granger, 1969).

From the definition of G-causality it follows that if a times series x G-causes a time series y that implies that some information has been transferred from x to y affecting the behavior of y. From a more formal perspective G-causality is not considered as an Information Theory measure (where Information Theory is the study of the computational quantification of information) but has strong similarities with well-known information theoretic concepts. For example, when variables are Gaussian distributed the G-causality method is equivalent to Transfer Entropy (Barnett, Barrett, & Seth, 2009), a method to compute (in information theoretic terms) the quantity of information flow between variables (Schreiber, 2000).

We define the quartet inter-musician communication (for a formal definition see Supplementary Methods) as the overall conditional G-causality within the quartet. Conditional G-causality is applied when more than two variables are examined. The conditional G-causality computes the G-causality of x on y conditioning on the remaining time series, i.e., taking into account (and thus removing) the possible influences (on y) of the remaining time series. Thus the overall conditional G-causality can be seen as the overall amount of "active" information (i.e., which affects the behavior of the musicians) transferred from musician to musician where the quantity of information from one musician to another is counted only once.

We define the driving force (see Supplementary Methods) of a musician A on a musician B as the difference between the G-causality exerted by A on B and the G-causality exerted by B on A. Thus a positive driving force of A on B indicates that A causes the behavior of B more than B causing A. The driving force of a single musician is defined as the average driving force of that musician on all the other musicians.

(Pairwise) G-causality and conditional G-causality were computed over the z-normalized time series of the Euclidian distances between the musician heads and the Ear of the quartet every 500 milliseconds (i.e., 2 Hz "sampling frequency") on 3-s sliding windows using the "Granger Causality connectivity analysis" Matlab toolbox (Seth, 2010). MDF and IMC were computed using the values of G-causality and conditional G-causality respectively, maintaining the same "sampling frequency".

Our analysis of the relations between IMC and MDF, and complexity and perturbations, imposed that IMC and MDF had the same sampling frequency as complexity and perturbation. Complexity and perturbation were annotated on the audio signal of the performance and thus had the sampling frequency of the audio signal. Since the sampling frequency of the audio signal was much higher than the sampling frequency of IMC and MDF (2 Hz) we oversampled and then interpolated IMC and MDF. Interpolation was carried out by inserting zeros into the new (value missing) samples and then applying a low-pass filter.

2.7. Statistical analyses

ICM and MDF parameters were submitted to statistical tests to draw inferences on them. The first step in the analyses verified the distribution of data and their variances to select the most appropriate statistical tests. Both ICM and MDF values do not follow a normal distribution according to normality tests (Kolmogorov–Smirnov). The variances were also not homogeneous according to statistical tests (Levene). Therefore, we used the two-tail independent samples Welch's t-test. In the Welch's t-test the assumption of normality is not critical for large samples (Geary, 1947) as is the case for our data set. More importantly, Welch developed an approximation method for comparing the means of two independent populations when their variances are not necessarily equal (Welch, 1947). Because Welch's modified t-test is not derived under the assumption of equal variances, it allows the comparison of two populations without first having to test for equal variances. Each p-level was corrected for multiple comparisons with the Bonferroni's method. Analyses were carried out separately for each take, due to inherent differences in length and interpretation given by musicians. Similar results across repetitions demonstrate the reliability of results. When allowed by data characteristics, the Friedman's test was applied on mean IMC or MDF values to all takes taken together. Friedman's test is a non-parametric randomized block analysis of variance. It does not require the assumptions of a normal distribution and of equal variances (of the residuals). All analyses were conducted using the Matlab Statistics toolbox (Mathworks Inc.).

The first set of analyses aimed at measuring the global inter-musician communication due to complexity in the score. Thus we compared IMC values between complex and non-complex segments within the normal (no perturbation) executions. A Welch's *t*-test was applied at the single take level, whereas the Friedman's test was applied on mean IMC values of each take.

The second set of analyses focused on the differential role played by musicians in driving ensemble behavior. MDF values were evaluated on pieces played with no perturbations. A Welch's *t*-test was applied at the single take level, both including all data and separating for complex and non complex segments. A Friedman's test was applied on mean MDF values of each take.

The third set of analyses instead focused on the effects of the perturbations on ICM and the first violin MDF. In order to do so, the score was first segmented in altered and unaltered sections. Then we replicated the same segmentation on the normal execution data set. In this manner we could compare the execution of the exact same musical segments both in the altered and unaltered versions. Since only the first violin knew the perturbations, we were interested in the specific modulations of MDF for the first violin only. Altered segments were concatenated across takes and compared with the same concatenated segments in the normal condition (Welch's *t*-test).

3. Results

The Kolmogorov–Smirnov test applied to the IMC as well as to the MDF values for both sessions of recordings, reported that no data set conformed to a normal distribution (See Supplementary Table 1). The Levene test applied to complex and non-complex segments reported no homogeneity of variances (See Supplementary Table 2).

3.1. The role of score complexity

The first set of analyses investigated the role of score complexity on the modulation of IMC (Fig. 2). Welch's *t*-test was applied to raw IMC data for each take separately. Results were highly significant for all takes (See Supplementary Table 3 and Fig. 2). The Friedman method was applied on mean IMC values for each take. This analysis reported a significant main effect of complexity on IMC values (Friedman's Chi^2 (DoF: 1, 9)$=$5; $p=0.0253$). Generally speaking we showed a clear pattern of increased IMC during complex segments.

3.2. The differential role of each musician

The second set of analyses investigated whether an implicit hierarchy or leadership could be derived from the data. Here we tested the modulation of MDF, across the five takes, between musicians. Pairwise Welch's *t*-tests have been applied (for detailed results see Supplementary Table 4) showing a repeatable pattern of MDF differences across takes (Fig. 3). The first violin was constantly excerpting a strong drive towards all other musicians (take 1, 2, 3 and 4) whereas the second violin was positively driving the others only in two takes out of five (4 and 5). Viola and Cello rarely (take 5) showed a large positive driving force. This Friedman analysis did not report a significant main effect of musician on MDF mean values (Friedman's Chi^2 (DoF: 3, 19)$=$4.92; $p=0.1777$). An analysis of the modulation of the musicians' MDF with complexity is presented in Supplementary materials (Supplementary Table 5 and Supplementary Fig. 3).

3.3. The effect of alterations

The third series of analyses focused on the application of perturbations to the normal communication pattern among musicians. A Welch *t*-test on IMC concatenated segments was run comparing altered and unaltered segments. Analyses showed a significant increase in Inter-Musician Communication during the altered segments (DoF$=$2794.67; $t=-3.2526$; $p=0.0011$). On the other hand, the first violin MDF was reduced when alterations were applied (DoF$=$2401.15; $t=6.6771$; $p=2.49\mathrm{e}-11$) (Fig. 4).

4. Discussion

Music coordination in quartets, when successful, produces one of the most engaging emotional experiences one could witness. However, measuring with standard behavioral methods the degree and temporal evolution of what makes this group of musicians be felt like a single-body entity, is quite challenging. Here, as initial approach, we applied Granger Causality analysis to musicians' head movements. The main result of our study is the clear relation between musical complexity and the amount of communication among musicians (IMC measures). Information flow, between all musicians as a group, was larger during segments characterized by difficulties in technical coordination. These effects corroborate our hypothesis that musicians coordinate behavior by maximizing their coordinative efforts in specific and critical moments in time.

Information transfer and thus sensori-motor communication was here conceived in the terms of Granger Causality. The Granger-Causality methodology tests whether knowledge of the past values of one time series significantly increases the prediction accuracy of the future state of another time series (Granger, 1969). In other terms, the algorithm measures whether one musician behavior has any influence on the behavior of another musician. However, it has to be noted that communication in any ecological scenario is always bi-directional. Therefore, one critical aspect of ecological sensori-motor communication is the ability to decode others' behavior and generate the appropriate signals to be decoded by the interacting participants. Along these lines, ensemble musicians could be a valuable tool to

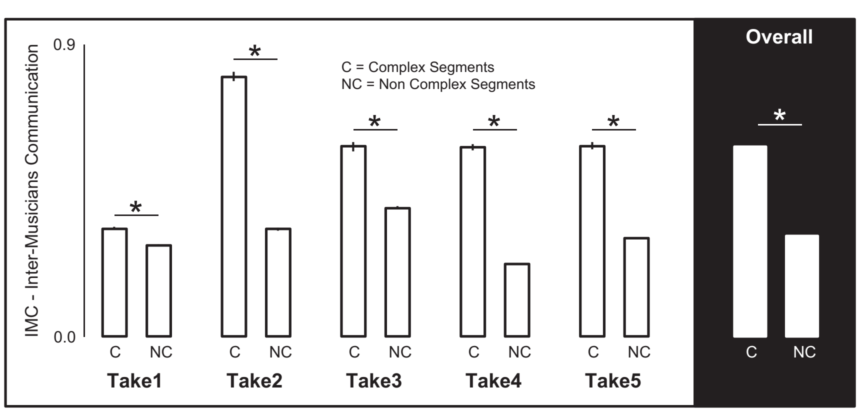

Fig. 2. Complexity effects on IMC. The histogram represents the amount of IMC for complex (C) and non-complex (NC) segments of music, separately for each of the five takes. Asterisks denote significant differences. In black background, the average over the different takes.

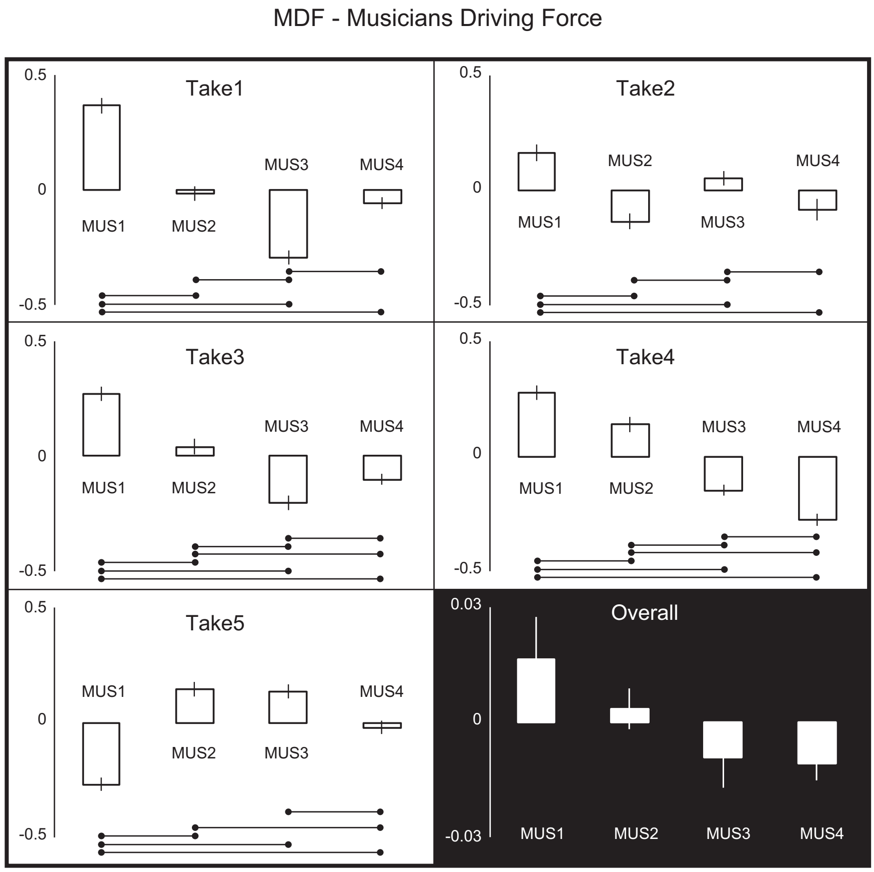

Fig. 3. Musicians differential role on MDF. The histograms represent the amount of MDF for each musician, separately for each of the five takes. In each sub-figure the lower bars represent significant comparisons. In black background, the average over the different takes.

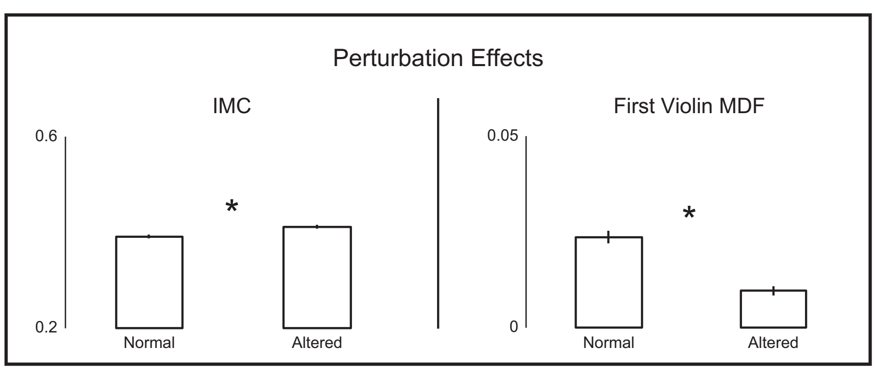

Fig. 4. Perturbation effects on IMC and first violin MDF. The histogram represents the IMC value differences between the same score segments with and without alteration. Alterations were known to the first violin only. On the right side the MDF from the first violin is compared in the two altered and normal situations.

study joint action control (Novembre, Ticini, Schütz-Bosbach, & Keller, 2012; Keller, Knoblich, & Repp, 2007). In fact, ensemble musicians can be seen both as pure experts in specific sensori-motor skills (Munte et al., 2002) as well as experts in social signal analyses (D'Ausilio et al., 2012; D'Ausilio, 2009)

More importantly, ecological sensori-motor communication is characterized by complex temporal and spatial dynamics. In fact, real interactions are often temporally superimposed and carried out by full body motions. Behavior complexity, together with almost negligible lags in performance (Kokal & Keysers, 2010) suggests that purely reactive mechanisms cannot be effective. Others' action anticipation is a necessary prerequisite for successful joint action control (Knoblich & Jordan, 2003; Pecenka & Keller, 2011). Generally speaking, expertise has been shown to support other's action classification by modeling future information earlier (Aglioti et al., 2008) and with greater detail (Calvo-Merino, Glaser, Grèzes, Passingham, & Haggard, 2005). Our musicians were almost at the top level of musical skills, thus suggesting that a strong degree of anticipation of others' action was taking place.

The mirror neuron mechanisms could probably support this kind of others' action anticipation. In fact, recent theoretical models suggest the predictive power of mirror-like activities (Friston et al., 2011), whereas neurophysiological research reported empirical evidences of others' actions anticipation in the observer's motor system (Kilner, Vargas, Duval, Blakemore, & Sirigu, 2004; Borroni, Montagna, Cerri, & Baldissera, 2005; Urgesi et al., 2010; Cattaneo et al., 2011). In agreement with these latter studies, research on joint action has provided evidence for the integration between actions planning of two agents, even when there was no need to take the other agent into account to perform the task (Sebanz, Knoblich, & Prinz, 2003; Sebanz, Knoblich, & Prinz, 2005; Sebanz, Bekkering, & Knoblich, 2006).

Other's action anticipation is a particularly important aspect, especially if we consider the problem of quartet coordination in the general framework of motor control literature. In fact, it is known in motor control research, that incoming information is not continuously monitored and used for control, due to inherent temporal delays in sensory signal (Jordan & Rumelhart, 1992; Wolpert, Ghahramani, & Jordan, 1995). Rather sensory feedback is internally modeled as sensory–motor pairs (Wolpert & Kawato, 1998), making sensory processing an active process of confirmation seeking from the environment. More importantly, the same mechanism has been suggested for others' action classification (Oztop, Kawato, & Arbib, 2012) and social interaction (Wolpert, Doya, & Kawato, 2003).

As a matter of facts, human motor control is fundamentally hierarchical. Higher up in the hierarchy, internal models become more and more independent from specific movement features thus encoding actions and behavioral goals (Wolpert et al., 2003). During social interaction, similar mechanisms can be modeled such that the controlled object is the other person rather than part of our body. In fact, our movements generate communicative signals that are sent to another person in order to influence her hidden (mental) state.

However, the very issue of measuring communicative signals and the subsequent effects on others' behavior is not a well-formalized problem. In fact, body movements are complex and several different features can be used in the analyses. Here we decided to use the distance between the heads of the musicians and the point where musicians reported music was perceptually generated during playing. In motor control terms, that was the point in space where the joint-action effects or inter-individual sensory goal states were generated. Thus, any coordinative action should have used that signal as a goal state. In fact, they were facing and directing their upper torso oscillations towards this point in space.

Concerning the analysis method, the Granger Causality algorithm could be only one of the possible methods to measure sensori-motor communication. Nevertheless, an interesting confirmation that our choice of features and method was reasonably correct came from our results. First of all we could show the emerging of an implicit hierarchy between musicians, with the first violin being most frequently the leader of the group (MDF measures). The leardership of the first violin should be regarded as the main leadership but the leader can change according to the musical segment and such leadership changes are identifiable by Granger Causality analysis (Glowinski, Badino, D'Ausilio, Camurri, & Fadiga, 2012). This is in agreement with the common string quartets' conventions and was certainly true for the Quartetto di Cremona. Furthermore, by applying unexpected perturbations to the communication pattern between the first violin and the rest of the quartet, we evidenced specific changes to both our measures. Inter-musician communication increased whereas the driving force originated from the first violin (the only one knowing when and what alteration to perform) decreased.

The perturbation forces an artificial and temporally confined change in the group dynamics. Such an approach, although it introduces a rather unnatural condition to the normal musical performance, is the only reliable method to infer a relation between our Causality-derived indexes and musicians' communication behavior. Specifically, the increase in inter-musician communication was probably a result of increased uncertainty and thus the need for a general increase in information transfer. On the other hand, behavior of the first violin was particularly interesting since he did reduce his drive towards other musicians.

This result can be interpreted in a more restricted manner by invoking the motor control framework outlined earlier. In fact, quartet musicians have one main source of common information, which is the score. The score, by definition, has the highest possible reliability. In parallel, musicians also build models of others' behavior. Strong musical expertise, as well as continuous rehearsal as an ensemble, certainly helps in increasing reliability and specificity of these models. In our perturbation approach, we suddenly make the score information almost useless and other's behavior less predictable. Therefore, musicians might need to shift from a mainly feed-forward control to a more feed-back based strategy and thus relying on a reactive behavior. However, as we discussed earlier, such a strategy do not permit fast and accurate motor control (Wolpert & Kawato, 1998) and multi-agent coordination (Wolpert et al., 2003). In fact, the advantage of modeling other's behavior is that we can anticipate and sample incoming sensory information less frequently and mainly to confirm our hypotheses on the environment. Therefore, our musicians probably had to completely shift their normal manner of communication, possibly “reading” others' behavioral cues and “sending” informative signals almost continuously. It may also be the case that musicians had to send/receive a complete different kind of message to cope for the novel situation. Therefore, the reduction in driving force from the first violin could follow from a reduced efficacy in communication caused by the abrupt shift from a novel and feed-back based strategy to a learned feed-forward manner of communication.

On the other hand the same result can be interpreted in a wider and more evocative manner. In fact, the perturbed scenario also adds one more interesting aspect, which is knowledge sharing between musicians. In fact, in the normal situation, musicians do share the score information as well as the past history of rehearsal, in a way that all necessary information for group performance is available to all members. On the other hand, the perturbed scenario artificially introduces an information unbalance between participants. The leader is now the sole possessor of some relevant information for group dynamics. In this case, as we described earlier, we force the need for unidirectional communication. However, the mere demonstration that the need for unidirectional communication is followed by a reduction in unidirectional information flow is particularly interesting. Indeed this could be interpreted as the demonstration that successful leadership, in driving group-level sensorimotor information flow, works better when all peer share the same amount of knowledge.

In conclusions, the present study obtained useful confirmations that a Granger Causality-based method on head oscillations does, at least in part, measure information flow between complex multi-agent interactions. Measuring the temporal deployment of sensori-motor communication between several individuals, in a realistic scenario, opens up to a series of important applications. In fact, current communication analyses hardly offer quantitative results when dealing with complex natural situations. The mere fact that we can quantify point-to-point information flow over time, may suggest that efficacy measures be derived from interacting individuals thus opening to a new quantitative science of communication. At the same time, our data hint to the fact that efficient sensori-motor communication, may not reside in the unspecific increase in information transfer. One intriguing possibility we suggest is that the fabric of expert interaction is not the ability to communicate per se, but rather the ability to modulate such information transfer when this is more necessary and among equally informed peers.

Acknowledgements

This work has been supported by European Union (EU) FP7 grant SIEMPRE awarded to L.F. and A.C., and EU FP7 grant

POETICON++ to L.F. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. The authors would like to thank the Quartetto di Cremona, for their professionalism and patience, Corrado Canepa and Chiara Noera for helpful discussions, Paolo Coletta and Simone Ghisio for working on the data recording, Eleonora Bartoli and Laura Maffongelli for their help on experimental setup.

Appendix A. Supplementary materials

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.neuropsychologia.2013.11.012.

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