Linking embodied coordination dynamics and subjective experiences in musical interactions: a renewed methodological paradigm

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Embodied music cognition provides a valuable and comprehensive research paradigm within systematic musicology to describe and explain musical sense-making. The basic claim underlying musical embodiment is that subjective meaning, in its broadest sense, is actively constructed within humans' bodily interaction with music. As such, the empirical study of bodily coordination may provide insights into the subjective aspects of musical experiences. In the present paper, we advocate for a dynamical systems approach to human music interaction, focusing on the time-varying principles, and the relational aspects of the musical interaction process. We propose a model that integrates these focus points, to investigate the link between embodied coordination dynamics, subjective experience and sense-making. We then discuss possible quantitative and qualitative techniques that allow to operationalise the model into concrete empirical music research. Finally, we conclude by presenting some illustrative research cases conducted at IPEM, Ghent University institute for systematic musicology.

Section 1: Introduction

"You are the music, while the music lasts"
(T.S. Eliot - Four Quartets, 1943)

Combining quantitative methods with qualitative methods or so-called mixed-method approaches can enable a deeper understanding of phenomena by gaining insights from multiple perspectives. However, we argue that their value is not found by merely searching for correlations in quantitative data and qualitative reports of subjective experiences. Instead, the central thesis of this paper is that this value is found by using appropriate procedures and routines that reveal interaction dynamics, meaningful constraints, relations and influences using the common vocabulary and theoretical framework of coordination dynamics.

The coupling of the quantitative and the qualitative has historically been a hotly debated topic (Sale et al.). From a pragmatic viewpoint, the discussion here is held while acknowledging the fact that research always occurs in a social, historical, political and cultural context (Bresler; Creswel) and stresses the fact that 'reality' is an ongoing, dynamical and meaningful transaction between environment, mind and sense perception (Barone and Pinar; Horne et al.). This discourse is situated in the domain of digital humanities and aims to extend the recently coined 'humanities 3.0' concept (Bod). As such, it acknowledges the value of using digital tools to discover patterns (humanities 2.0) alongside hermeneutic and critical approaches (humanities 1.0) but argues that one should go beyond mere patterns and focus on the underlying principles that create them.

Both qualitative and quantitative methods are valuable and necessary approaches to gain knowledge. In any research domain, qualitative and quantitative approaches have shown their value as respectively inductive and deductive instruments (Creswel). Qualitative research allows for a deeper understanding and appreciation of phenomena while quantitative research provides a more precise analysis and prediction with the goal of generalisation (Razafsha et al.). In addition, quantitative methods feature a larger distance between researcher and research, exchanging meaning for a higher level of abstraction. However, both are systematic attempts to examine concepts (Razafsha et al.; Bodie and Fitch-Hauser). Simply put, quantitative methods are particularly powerful in discovering patterns in occurring phenomena (regularities, inter-dependencies, trends), while qualitative methods are particularly well suited for interpreting the found patterns. The combination of quantitative and qualitative data provides additional insights and is now widely applied in research using mixed-method paradigms (Creswel). However, as both methodologies study different phenomena, combinations should remain complementary and should not be used for cross-validation (Sale et al.). We assume this mixed-method approach here complemented by the vocabulary and features of dynamic systems theory. From the latter we use non-linear quantitative methods for pattern discovery and argue for the use of qualitative methods for their interpretation.

In the present article, we want to contribute to the debate on human interaction with music. In accordance with the embodied music cognition (EMC) paradigm that will be introduced in section 2, we approach musical meaning as an active process: a lived experience, created in-the-moment of people's interaction with music and situated in a specific socio-cultural context and personal 'histories' of experiences (Leman, *Embodied Music Cognition and Mediation Technology*; Cook). The human body, its motor and (neuro)physiological functioning are thereby attributed a central role. The core assumption is that the observation of the body, and its functioning, may provide access to the subjective realm of musical experience, feelings, and sense-making. In that regard, observable patterns of bodily activity and the subjectively felt quality of that interaction are essentially coupled, making the integrated use of quantitative and qualitative methods necessary. Supported by new technologies for measuring bodily activity (movement, physiology and brain activation) and computational analysis methods, empirical research has profoundly ameliorated our knowledge on the embodied basis of human music interaction (Lesaffre et al.). Yet, some important challenges lie ahead.

A first challenge pertains to the enormous variability in the observed patterns of embodied music interaction, both in time and space, complicated further by the manifold contextual and personal factors. Given this variability it is hard to interpret and generalise musical behaviours and experiences. Typically, the solution is found in a reductionist approach stripping away the lived experience of a real-life musical interaction to a greater or lesser extent. Yet, it's hardly ascertainable that variation, deviation, dynamical change and surprise are at the core of musical pleasure and sense-making. For this reason, this article approaches human beings and their musical environment as a complex adaptive system, seen from the dynamical systems paradigm. The core insight we adopt from the dynamical systems paradigm is that, instead of looking at the appearance of patterns in their manifold variability, we need to focus on the understanding of the organisational principles that lead to the manifold observable patterns of music interaction. It is here that quantitative methods can help in the detection and analysis of patterns while qualitative methods can help with their interpretation and reveal the relation to their underlying organisational principles. According to the paradigm, these principles are generic, regulating pattern formations in physical and biological systems nature-wide. This includes systems that involve human embodied interaction and the subjectively felt qualities of these interactions. What is especially interesting is that dynamics, variability and instability are at the core of these organisational principles in order to allow systems to behave flexible, adapt to change and evolve towards qualitatively new forms of organisation and behaviour. Finally, the dynamical systems paradigm provides a valuable vocabulary, giving the opportunity to connect the languages of people involved in music interactions (interpreters) with music and cognitive (neuro)science (pattern finders). The methodological model incorporating these notions from dynamic systems and EMC forms the content of section 3. A selection of quantitative techniques used for pattern detection and analysis are discussed and introduced in subsection 3.1.

Secondly, we need to deepen our knowledge on the nature of the subjective experience of human interaction with and via music. Early attempts of investigation, which were rooted in the domain of phenomenology (Pike; Dura) will be introduced alongside the EMC paradigm in section 2. The original objective of phenomenology is the systematic attempt to uncover and describe the internal meaning structures of a lived experience (Van Manen). Qualitative methods seem best suited to undertake this task, given that the study of an experience is primarily approached from a first-person perspective (F. J. Smith; Gallagher; Randles). Nevertheless, the complementarity of seemingly decoupled opposites such as the quantitative and qualitative has historically been included in the phenomenological view.

Phenomenology arose out of the need to bridge Cartesian dualism between objects 'out there' and subjectivity 'in here' (Kearney). A deeper elaboration on this view may foster the development of innovative methods for the integrated study of quantitative and qualitative aspects of human music interaction (Schäfer et al.). To this end, more recent psychological and neuroscientific accounts on the quantitative study of subjective experience are discussed in section 3.2.

Finally, we end this paper with a section on four research experiences which incorporate the methodological model from section 3 in their practice. While some of them are still on-going, they aim to illustrate how the quantitative and qualitative techniques from subsections 3.1 and 3.2 can be used in empirical research of dynamical music interactions.

Section 2: Theoretical background

The goal of this paper is to present a model, implementing a renewed methodological paradigm to study dynamical musical interaction processes. An essential feature of this paradigm is the aim to link quantitative coordination *patterns* characterising a musical interaction, to the subjectively felt *quality* of the interaction. The realisation of this paradigm relies on the combination of different theoretical frameworks. At the core lies the EMC theory that provides a global theory on the intricate relationship between bodily movement and subjective sense-making. As an extension, we propose to integrate the theory on coordination dynamics, as it allows us to deal with the spatiotemporal variability and complexity inherent to musical interactions, by focusing on the generic structuring principles underlying musical interactions. Finally, we refer to the framework of phenomenology, as a means to integrate a first-person perspective to the experienced quality of a musical interaction, linked to the concepts of intentionality and agency.

Embodied music cognition EMC is rooted in more general theories on embodied cognition and interaction (Varela and Thompson; Anderson) and embodied forms of phenomenology (Merleau-Ponty). These theories have led to several complements and extensions such as in the enactive, extended, embedded, ecological, emotional, engaged, expressive and emergent approaches (Hutto and McGivern).

Core concepts of all these approaches are the close action-perception coupling and the interaction with the environment.

The core idea of EMC is that an intentional level of musical interaction is established through corporeal articulations and imitations of sensed physical information provided by the musical environment (Leman, *Embodied Music Cognition and Mediation Technology*). It emphasises the role of the human body as mediator for meaning-formation and places it in an interconnected network of sensory, motor, affective, and cognitive systems involved in music perception. Subsequent accounts have extended the role of environmental and social contexts by emphasising the importance of collaborative interaction and joint action (Moran). These contexts would enable a sense of participatory sense-making, creativity, meaning-formation (De Jaegher and Di Paolo) and intense subjective experiences (Maes et al.). Others have highlighted the overly dualistic nature of a 'body as mediator' and in the distinction between encoding and decoding, nature and culture (Geeves and Sutton).

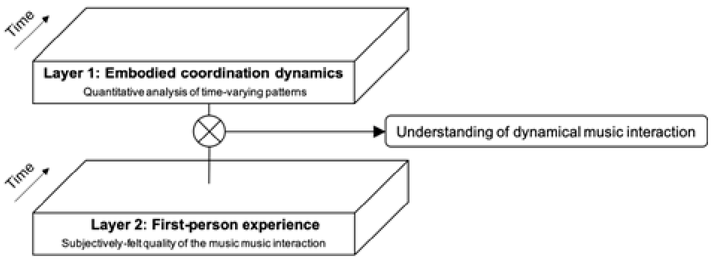
The EMC framework is valuable in the way it connects subjective experience and sense-making to situated bodily activity. However, empirical research has generally been struggling to reliably capture the complexities and variability, both in time and space, inherent to embodied musical interactions. A solution that gains increasing impact is to extend the EMC framework with a more dynamical account to music interactions. Within our proposed methodological paradigm, we integrate the interdisciplinary framework of coordination dynamics, originating in the work of JA Scott Kelso, to better capture the complexities and spatiotemporal variability in embodied music interactions.

Coordination dynamics is a theoretical, methodological and analytical framework that aims to understand how patterns of coordinated behaviour emerge, persist, and evolve in living things (Kelso). This line of scientific inquiry focuses especially on time-varying coordination processes in the human brain and behaviour, making it particularly applicable to the study of embodiment in dynamical musical interactions (Borgo; A. Demos et al.; A. P. Demos et al.; Maes; Varni et al.; Walton, Washburn, et al.). Musical interactions, whether in performance or dance, require an intricate, fine-tuned spatiotemporal coordination of a large number of coupled body parts (of one or more individuals) to reach a coherent and pleasant performance. According to the coordination dynamics approach, understanding the temporal dynamics of such musical interactions is to study the *relationships* that exist between the individual bodies and body parts, rather than studying them each on their own. In other words, bodies and body parts should be studied as a collective system and correspondingly, the unit of analysis should be shifted to the system level. The central thesis thereby is that such a system will self-organise throughout time so that quasi-stable relationships and patterns are established between its interrelated parts. The field of coordination dynamics is thereby of interest for music research as it provides valuable analytical tools to quantify the time-varying relationships and patterns within complex, coordinated musical behaviour. In addition, coordination dynamics brings in a scientific vocabulary of concepts that is suited to match the vocabulary of musicians and dancers, describing their musical experience often in terms of a dynamic interplay of moments of relaxation and tension, balance and instability, complexity and simplicity, predictability and surprise.

Phenomenology A third theoretical underpinning inherent to our proposed methodological paradigm for studying dynamical musical interaction is the framework of phenomenology. Phenomenology provides a stepping stone to the integration of a first-person perspective to the experienced quality of an embodied (musical) interaction (D. W. Smith; Gallagher). A shared importance between phenomenology and the approach presented here is given to the role of the body. Merleau-Ponty, for example, focused on the circular relationship between the objective and subjective dimensions of the body that enable a relation between the perceiving and the perceived (Halák). Concepts such as empathy and inter-subjectivity that are crucial in any musical interaction rely on this relationship (Zahavi; Duranti). Another relevant phenomenological concept is that of perceptual indeterminacy (Merleau-Ponty). It can be linked to the aforementioned positive traits of variability and instability of a dynamical system as it views the indeterminate as a positive phenomenon from which qualities can emerge. As such, it also shows a correspondence with the concept of emergence in dynamic systems (De Wolf and Holvoet) and meta-stability in coordination dynamics (Kelso). A concrete musical example is the emergence of 'groove' out of small time-differences in music (Roholt). A phenomenological account by Casey illustrates the value of investigating the subjective experience in musical contexts.

The musical experience is said to be direct, involving a 'willing suspension of belief' through the practice of so-called 'bracketing' as stated in phenomenological reductionism (Casey). Interactive musical scenarios as experimental settings could thus provide transparent investigations into the subjective experience by minimising noise from spurious mental processes and thoughts. Some neuroscientific accounts comment on the illusionary experience of a phenomenological unity in the musical experience when perceptual components such as pitch, rhythm, tempo, meter, contour, loudness, spatial location and timbre are processed separately (Niedenthal et al.; Levitin and Tirovolas). These accounts stress the experiential aspect of music but nevertheless remain vague as to how this experience comes about. Below, we will discuss some possible methods to assess the subjectively experienced quality of musical interactions from a first-person perspective.

Section 3: A renewed model for linking embodied coordination dynamics and subjective experiences



The three theoretical frameworks are combined into a working model, proposed as a methodological paradigm for the empirical study of dynamical human music interactions. As mentioned, the model is rooted in the EMC theory in the sense that human experience and sense-making (layer 2) is inherently linked to bodily action and interaction (layer 1). Yet, the model proposes to extend this basis of the EMC theory in a twofold manner. As a first extension, the model attaches great importance to the time-varying nature of embodied music interactions and their subjective experiences. As a second extension, the model advocates for a systems perspective to the study of human music interaction. As explained above, embodied coordination and sense-making are understood as collective, participatory, and relational processes.

On the level of embodied coordination dynamics (layer 1), the challenge is to better understand how humans jointly construct patterns of order (articulated in bodily movement and sound), and how these patterns sustain, break down, and evolve towards new ordered patterns throughout time. On the level of the first-person experience (layer 2), the challenge is to better understand the affective quality of the joint relationship between interacting musicians, dancers or listeners. This affective quality pertains to the communicating and negotiating of intentions, to expressivity, the feeling of togetherness, shared agency and flow among other experiential aspects. Finally, the key challenge related to the model is the investigation if, and how, the time-varying patterns of embodied coordination relate to the affective quality experienced by the musicians, dancers, or listeners involved. This final challenge might include an analysis at multiple levels of observation, for example from body part to individual or group level, and lead to a verifiable formalisation of underlying organisational principles.

In concept, it is increasingly acknowledged within the cognitive and social sciences that the time dimension and (dynamical) systems approach are relevant in research on human interaction. So far however, empirical research in the domain of music has experienced difficulties to reliably capture the time-varying processes in concrete scenarios of human music interaction. An important goal of the present paper is to briefly discuss existing methods that provide opportunities for empirical research, enabling ourselves to operationalise ideas inherent to the model presented here.

Layer 1: Quantitative measurement and analysis of embodied coordination dynamics

With increasing technological innovation, researchers now have a wide-ranging choice of tools and sensors for capturing quantitative data. This wealth of possible data poses a considerable challenge to researchers to decide on the most relevant data and eliminate noise given the envisioned research questions. In the context of music, data may pertain to audio recordings, body movements, physiological data, note sequences and many more. In this section, we introduce five quantitative techniques that are well suited to unveil time-varying patterns and processes in sequential, non-stationary and time-series data. As such, they are proper candidates to operationalise layer 1 of our model proposed above. The discussed techniques allow us not only to unveil time-varying patterns within a single time series, but equally to unveil patterns across, and relationships between multiple data streams. This makes them particularly relevant to implement the systems approach advocated for in our model. In addition, working with dynamic systems re-values outliers and individualised research through its capability of working with multiple resolutions (Holmes et al. 2013; Bresler 2006). It allows us to uncover underlying simple principles while keeping in mind intrinsic dynamics and initial conditions. It tackles the challenge of too many degrees of freedom by focusing on lower-dimensional order parameters. All these challenges are characteristic of non-linear interactions. It is a goal of the methods below to reveal the recurrent patterns, underlying structure and more general, understand the interactions between components.

Phase space reconstruction makes it possible to identify patterns and relations between non-recorded degrees of freedom. It refers to the process of obtaining the phase space of a dynamical system from its time-series. A phase space represents the set of all possible states of a dynamical system such that each state of the system corresponds to a unique point in the state space. Using an influential theorem, one can reconstruct this space using a potentially lower-dimensional time-series (Takens).

An example can be seen in figure 5. On the left, it shows a one degree of freedom gyroscope recording of a simple movement with a smartphone. On the right, it shows its associated phase space reconstruction and three-dimensional patterns corresponding to pitch, yaw and roll.

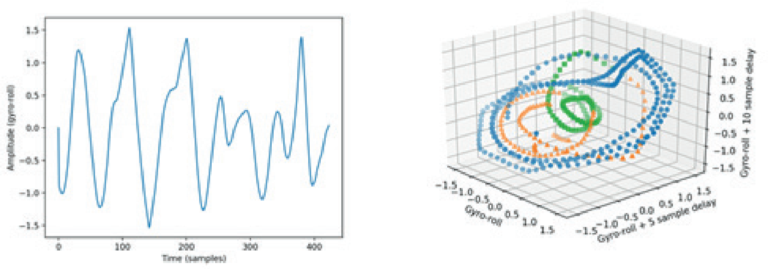


Figure 5: Gyroscope data recording of 1 degree of freedom (left) and its phase space reconstruction (right)

Recurrent Quantification Analysis This technique allows scientists to reveal structure in complex time-series. It takes the reconstructed phase trajectory of a dynamical system and counts the number of recurrences to any particular state. Its basis is a square distance matrix with recurrence elements evaluated using a cut-off limit called a recurrence plot. The advantage of this technique is that it does not require assumptions about data stationarity, data set size or distribution.

Figure 6 shows example recurrence plots with phase space trajectories on the x- and y-axes from conditions in which two subjects are instructed to tap their hand along with metronomes. The metronomes start in-phase but gradually de-phase due to different tempi. The left-most plot shows the trajectory of the metronomes' relative phase and shows a predictable system that linearly increases its collective variable. The plots in the middle and to the right respectively show the participants in isolation and looking at each other's hand moving. It shows how variability in human behaviour adds random fluctuations and structure at specific time- and phase-relationships.

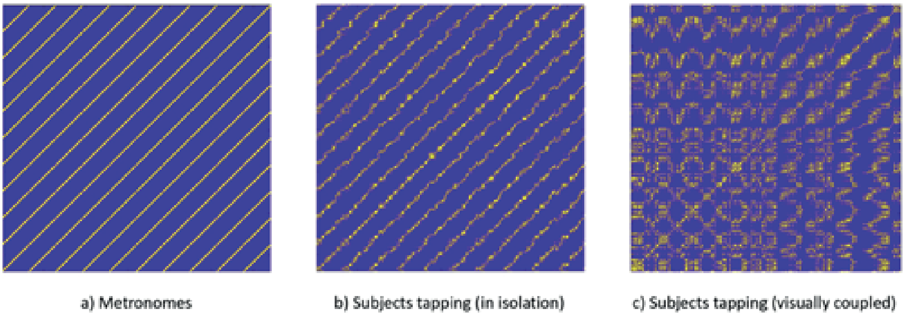


Figure 6: Recurrence Plots (RPs) computed from the time series of a system's collective variable (relative phase)

Fractal analysis Fractal analysis represents a collection of contemporary methods that measure complexity. It is useful in measuring properties of systems that possess a degree of randomness and makes it possible to simplify and quantify complex relationships over multiple spatiotemporal scales. For example, it has been used to show the ability of listeners to predict tempo fluctuations (Rankin et al.), to measure complexity in musical improvisation (Keller et al.) and to describe gait dynamics synchronised to music (Hunt et al.). An important measure is the fractal dimension, which evaluates to what extent properties depend on the resolution at which they are measured. Another technique that is often used is called Detrended Fluctuation Analysis (Peng et al.). It calculates a curve with an exponent that is an indicator of structure appearing at multiple scales (self-similarity), long-memory processes, 1/f noise and power-law relationships.

Cross wavelet coherence This technique is useful to assess synchronisation between subjects. It evaluates coordination through examination of the strength (coherence) and patterning (relative phase) of two time-series across multiple time scales. It can be applied to non-stationary data and is a form of spectral analysis for non-linear timeseries. It is able to reveal periodicities of local micro-scale structures within global macro-scale patterns (Walton, Richardson, et al.). An example of a plot of the transform is shown in fig 7 and was used to assess coordination using movement data of two players playing a shaker instrument. It indicates a higher degree of synchronisation for lower frequencies (0.125Hz or 8 second period) and a regular phase-lag (a quarter cycle or 2 seconds) between the two players indicated by the upward arrows. This observation can then be related back to the musical phrases and their interpretation by the musicians.

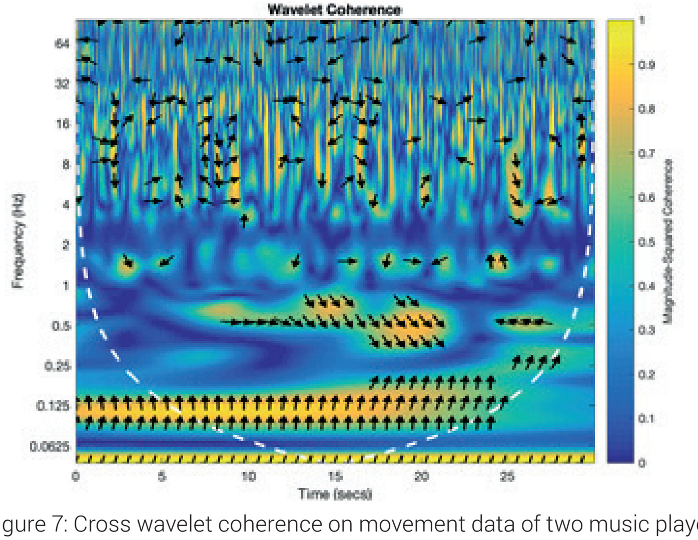


Figure 7: Cross wavelet coherence on movement data of two music players

Dynamic models When relevant (control and order) parameters have been defined and an in-depth understanding of the non-linear coupling between components has been achieved, one can formulate a mathematical formulation of a dynamic model. They are useful for prediction and allow a deeper understanding of phenomena through their formalisation of a general organisational principle. They can be experimentally tested and are built upon simple dynamic models. To name a few, models exist for rhythm perception (Large), synchronisation (Mörtl et al.) or join-action (A.P. Demos et al.).

The presented techniques obviously do not represent an exhaustive review of techniques for non-linear analysis of dynamic systems. Neural networks might be used to learn underlying dynamics without defining an explicit internal model beforehand. Other (linear) movement analysis methods based on principal components (Toiviainen et al.), topological structure (Naveda and Leman), probabilistic (Sievers et al.), sequential (Françoise et al.) or functional (Caramiaux et al.) models have shown their value but do not capture fine-grained spatiotemporal structures or non-stationary data well. Linear methods such as Fourier analysis, auto- and cross-correlation can provide helpful directions for subsequent analysis. A good evaluation of the use of both linear and non-linear methods is given (Ravignani and Norton) in the context of measuring rhythm complexity.

Layer 2: Assessment of the subjectively experienced interaction quality

In this sub-section we intend to raise an important methodological problem in the study of subjective experience, namely its operationalisation in experimental settings. How can we translate the subjective experience into observable variables, in order to measure some dimensions of the subjective experience without interfering with the experience itself?

Partial solutions to tackle such a big problem are already available for adoption. They are presented here as a non-exhaustive methodological overview with practical suggestions for empirical music research. At this layer, the researcher is confronted with the methodological challenge of organically integrating the assessment of subjective experience and the measurements of dynamics recorded during musical interactions. As we stressed over the course of the present article, this integration is a condition necessary for a deeper understanding of the phenomenon.

Questionnaires and scales

The first point worth clarifying is the validity of verbal reports from the subjects as quantitative data, as we often rely on their content to measure dimensions of the first-person experience. Interrogating the subject about its own awareness is so far the most direct form of access to the experience: in-depth interviews, focus groups, questionnaires, concept mapping, focused life history narrative, audio/video/document analyses, documentary analysis and case studies can provide access to the domain of subjective experience (Razafsha et al.).

Nevertheless, when it comes to measuring the quality of an ongoing interaction, verbal reports suffer from the intrinsic disadvantage of being mediated by self-referential cognitive processes that eventually lead to verbalisation. This implies this sort of data cannot be collected without perturbing or interrupting the flow of the interaction. Hence, there is a need for the report to be referred to a posteriori with respect to the original experience. The solution is sub-optimal, as the subject would refer to a memory of the experience rather than to the experience itself. Furthermore, reports collected a posteriori are usually a summary that are difficult to relate to the time-varying nature of interactions.

Time-varying ratings

In order to facilitate the mediation between the participant and its experience at the time of the measurement, video-audio stimulated recall is a valid approach which has been proposed in music research (Desmet et al.; Caruso et al.). It consists of presenting to the participant a recording of his own performance, so that he or she can associate freely, coming up with expressions and intentions to specific moments of the experimental session. An annotation system is then provided to continuously rate subjective parameters of interest over the course of the stimulation to generate a time-series that can be related to the time-varying measures recorded from the interaction. A practical use-case for annotation will be presented in the next section.

We want to point out that the variable to measure should be carefully selected, since repeating the procedure several times can be tedious for the participants and compromise its own reliability. Since the approach provides measurements that are limited in richness and nuances of content, the researcher should ideally collect as much information as possible by complementary and less systematic means. Open questionnaires and interviews at the end of the session give the participant the opportunity to elaborate on some crucial moment of the experienced interaction, which is potentially a valuable source of information on attributed meanings.

Inference from physiological markers

Besides the above-mentioned methods and based on processes of intentional evaluation by the participant, disposing of a 'toolkit' of sensors for measuring biomarkers can provide the researcher with access to some low-level dimensions of the subjective experience. For instance, analysing the electroencephalogram (EEG) of a person presented with subliminal stimuli can be enough to know whether the stimuli were consciously perceived or not, without asking for any verbal report (Dehaene). Very far from being any sort of 'mind reading', the approach consists of looking for physiological patterns of activations that work as a 'signature' for relatively low-level dimensions of consciousness.

The set of tools for the detection of physiological markers spans the central, peripheral and autonomic levels of the nervous system (Steinbeis et al.; Grewe et al.). Electromyography (Ekman; Tamietto et al.), pupillometry (Laeng et al.), electro-dermal activity, heart-rate and blood pressure among others (Critchley), have widely proven to provide valid signatures of some components of subjective experience. Over the years, all of these peripheral measures have been correlated to regional brain activity in order to shed light on the hypothesis of so-called 'somatic markers'. Such quantifiable markers represent states of body arousal which are integrated in the brain to give rise to emergent feeling in the immediate experience of the here-and-now (Damasio).

We want to stress that physiology can give access to low-level dimensions of conscious experience, such as arousal and basic emotions. Higher-level processes such as meaning attribution and interpretation are out of the reach of these techniques when they are not combined with subjective reports.

Section 4: Cases

What follows is a summary of some ongoing studies carried out by the researchers at IPEM, whose line of research is inspired by the integration of coordination dynamics into EMC. Questions they attempt to answer can be summarised as follows: how is coordinated behaviour structured and evolving over time? How do individual actions lead to the emergence of stable forms of coordination between interacting people? How can we interpret the patterns observed in an experiment in light of the participants' subjective experience? And, most importantly, how can we design interactive experimental scenarios in light of the methodological reflections presented in previous sections of this paper?

Joint musical interactions *(A. Dell'Anna)*

In the context of musical interactions, the concept of '*homeostasis*' was proposed as a stable state characterised by an optimal equilibrium of behavioural, physiological and subjective parameters within a system (Leman, *The Expressive Moment: How Interaction (with Music) Shapes Human Empowerment*). According to the proposal, the quality of a collective performance directly depends on the behavioural stability of the individual parts engaged in the interaction. In order to test the validity of such a construct, dell'Anna (under revision) designed a novel dyadic singing task inspired by the medieval Hocket technique: each participant is provided with a musical score, such that the partners have to alternate with one another in singing individual notes in order to form together the global pattern of the song.

After the task, both participants are presented with audio-visual recordings of their joint performance and asked to continuously move a slider up and down to rate the quality of the interaction. As we previously mentioned, such approach makes it possible to correlate the course of the performance to a time-varying series of subjective ratings, instead of entirely relying on questionnaires which fail to grasp the evolution of the experience over time. Furthermore, presenting the recorded performance to the participants implies that they do not have to rely solely on their memory for the assessment. In this sense, the method attempts to minimise the mediation between the actual experience and the moment when a participant is asked to recall it.

The influence of Carnatic dance of intentionality in piano performance *(G. Caruso)*

The author of this study is a professional pianist who dedicated her PhD project to the integration of performer's self-reports into the EMC framework (Caruso et al.). Starting from the EMC notion of mediation, she investigates how performer's intentions are translated into observable actions and adds a reflective method to assist the artistic practice. She defines a two-way process of bottom-up processing, based on quantitative recordings of a performance, and top-down processing consisting of qualitative annotations from the performer.

The latter component of the process is defined as *performer-based analysis* and is based on the methods of stimulated recall (Bloom) and thinking-aloud (Van Den Haak et al.). In such a way the performer provides structural, interpretative and technical annotations to her own recorded performance (first person perspective) and combines these with extracted features and patterns using quantitative methods (third person perspective). This method is closely related to the paradigm presented in this paper as the performer-based analysis allows for the visualisation of gesture-sound performance patterns with their interpretation through annotations of gesture-sound intentions. An additional step could be a more dynamic account of this approach incorporating non-linear aspects of emergence, self-organisation and sudden (non-linear) qualitative shifts in both the experience and the performance. Such an approach would account for the time-varying feedback loops occurring between the performance and the performer's experience.

Neural bases of coordinated collective behaviour *(M. Rosso)*

Over the past year, one of the authors of the present article started his project adopting a joint finger-tapping task for dyads of participants, during which their brain activity is recorded by means of electroencephalography (EEG). The main goal of the project is to investigate what changes in the brain activity of two people when they pass from behaving as individual units to behaving as a coupled system. In the paradigm, each participant is instructed to tap the index finger on a sensor, keeping the tempo of a metronome. Depending on the condition, participants can see each other's actions, hear each other's actions or perform the task in isolation. The way the metronomes are programmed is meant to lead the two participants to dynamically explore a whole set of coordinative states over time, recurrently creating a conflict between the timing they are instructed to keep and the timing of the partner's actions. When participants are coupled via a sensory modality, we observed the emergence of spontaneous reciprocal attraction leading to stable coordinative behaviour despite instructions to ignore each other.

Brain dynamics taking place over the course of the interaction are systematically related to the time course of collective behaviour, to its stable states and to its transitions. Questionnaires are introduced at the end of experimental blocks to make sense of the observed patterns in light of the subjective interpretation of the participants. For instance, observed patterns of interpersonal coordination can be experienced as the result of either a cooperative or competitive process. The distinction implies that very different cognitive processes can account for similar observed coordinative patterns, hence the need for orienting and interpreting the analysis of brain dynamics in light of qualitative data.

Simulating musical interactions in virtual reality

(B. van Kerrebroeck)

The aim of this ongoing study is to investigate the simulation potential of a musical interaction. Its motivation is the search for new, immersive experimental scenarios allowing for careful measurement and control of experimental stimuli and to offer insights in technology-mediated (musical) interactions. The study uses virtual reality to compare settings in which a pianist plays with a live or a virtually recorded version of another pianist. The recorded pianist is controlled using principles of coordination dynamics to enable a realistic behaviour. Concretely, it allows the recording to adapt its tempo and playing position in the score based on the playing of the other pianist. To evaluate the simulation, we record behavioural data such as the timing of notes and player movement as well as physiological data such as pupil dilatation and gaze direction. This quantitative data is complemented with a questionnaire gauging experiential aspects of presence, flow and immersion together with annotations using the performer-based analysis method. Non-linear techniques such as the ones presented in section 3.2 are then used to identify occurring patterns in the interaction (that is, in the behavioural and physiological data) and enriched with interpretations using the recorded qualitative data.

Section 5: Conclusion

The main contribution of the present work is the proposal of an approach to orienting methodological solutions in music research. This approach aims to integrate the dynamic and non-linear aspects from coordination dynamics with the embodied music cognition framework. In addition, it stresses the use of qualitative data from first person perspectives complementing quantitative methods to achieve a better understanding of complex phenomena at a systems level.

Interactions between brains and bodies can nowadays be quantified, described and modelled at a millisecond scale (Heggli et al.) and show emergent patterns that they underlie. Bringing the model described in this paper into music research might shed light on the organisational principles underlying patterns in complex cultural phenomena such as musical interactions. A theory-driven use of the tools at the researcher's disposal is an opportunity to contribute to the hermeneutical turn in Digital Humanities 3.0 (Bod). In line with the Embodied Music Cognition theory, we argue that emergent patterns can be better understood by building a knowledge of the time-varying dynamics occurring at the level of the body, conceived as the mediator of interactions with sound and music (Leman, *Embodied Music Cognition and Mediation Technology*). The experimental design in this line of investigation would ideally develop interactive scenarios that bring together physiological measures, motion analysis and subjective assessment in a way that minimises the inevitable mediation of the experience due to the measurement. Some operational steps in this direction have been initiated, for instance with the performer-inspired analysis (Desmet et al.) and the use of motion capture to 'mirror' intentionality in musical performance (Caruso et al.). In parallel, the corpus of existing literature on joint action spanning from the simplest forms of rhythmic interactions (Konvalinka and Roepstorff) to actual musical practice (Sänger et al.) provides a solid grounding for extending the study of dyads or groups of subjects as interacting systems organised by coordination dynamics. Current empirical music research already employs elements of the model presented here. However, a further cross-disciplinary approach guided by an integration of these different elements might lead to a new and deeper understanding of musical interactions.

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