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Embodying dynamical systems in music performance

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ABSTRACT: The present contribution introduces a theoretical framework to explore music performance from a perspective inspired by the conceptual resources of two orientations known as *Dynamical System Theory* and *Embodied Cognitive Science*. We discursively elaborate on how music performance might be conceived of as a complex, multi-component system that deals with evolving patterns of stability and instability, and examine how a combination of cognitive, motor, and affective skills stands at the heart of the performer's capacity to optimize their performance. In doing so, we consider how musicians often generate different interpretative "hypotheses" with little or no pre-planning and use their body to selectively navigate the range of possibilities such hypotheses entail. In conclusion, the relevance of this perspective is discussed in relation to current research in music performance and music education to outline continuities and differences between the two domains.

KEY WORDS: music performance, dynamical systems theory, embodied music cognition, affordances, musical instrument.

INTRODUCTION

Think of a classical musician (e.g., a violinist) performing a solo piece during a recital. Imagine being there from the beginning to the end of the concert. What do you see and hear? Typically, this situation involves the musician, the instrument, the score, the audience, the concert hall and, of course, the music they play. All these components, whether they are fully manifest or more hidden, contribute to determining the overall musical outcome. In other words, to varying degrees and over different times-scales, musicians need to deal with, and adequately respond to, these (and other) bodily, material, and environmental factors to deliver a meaningful performance. For example, the temperature of the concert hall may affect the tension of the strings, which in turn has an impact on the bowing and on the performance (e.g., outcome, experience) more generally. Similarly, changes in how the audience participates in the musical event (e.g., in terms of the intensity of their applause after each piece) might give the musician more, or less, confidence, affecting many musical choices in the following pieces. Examining music performance through such a synergistic view trades the focus on the musician's own cognitive and decision-making processes for a more *dynamical* perspective that incorporates a range of other factors that include, but extend beyond, the performer themselves (Bremmer & Nijs, 2020; Demos et al., 2014; Large, 2000).

In many ways, previous research on musical performance has placed a main emphasis on the modes of engagement between a performer and the musical material, focussing on the musician's action and bodily movements (e.g., Davidson, 1993, 2005, 2012), the score (e.g., Timmers & Honing, 2002), the interaction between performers (e.g., Glowinski et al., 2015), the responses of the audience (e.g., Pitts, 2005), the (qualities of the) musical material being produced (e.g., Lerch et al., 2020) or the social, economic, and political context in which a specific performance takes place (e.g., Turino, 2008). While we recognise the value of such scholarship and its important contribution to the field, we also acknowledge that the analytical distinctions between these main themes may play down the fundamentally holistic dynamics of music making (e.g., Elliott & Silverman, 2015; Small, 2008). As such, the conceptual tools of systems thinking (e.g., Ramage & Shipp, 2009) and *dynamical systems theory* (e.g., Chemero, 2009), might offer a new understanding of music performance, which better captures what music performance experience entails. From this dynamical perspective, the synergistic relationship between musicians and their social and material environments is examined as the context in which musical meaning plays out (van der Schyff et al., 2018; Walton et al., 2014). While this approach has inspired new understandings of specific features of music-making, such as musical gestures, creativity, emotions, empathy, and musical timing and interaction (Borgo, 2022; van der Schyff et al., 2022), a more encompassing view of music-performance-as-a-whole arguably remains underdeveloped.

The present contribution aims to help fill this gap by laying out a preliminary framework for examining musical performance through this dynamical lens. To do so, we aim (i) to illustrate how music performance might be conceived of as a complex, multi-component system that deals with evolving patterns of stability and instability; and (ii) to examine how a combination of cognitive, motor, and affective skills (Leman, 2017) stands at the heart of the performers' capacity to navigate such a web of relations, to optimize their performance.

In exploring this bidirectional dependency – where a musician shapes and is shaped by the different components of such a system – our focus will be on score-based performance in the tradition of Western classical music. We are aware that this is a rather limited scope, and that it represents only one specific cultural and pedagogical tradition; however, given its impact on music scholarship, it offers us a valid starting point to provide novel insights that can be extended to other traditions and communities of practice.

In the next section, we introduce this systemic orientation by identifying the different components that constitute the phenomenon we call "music performance". By doing so, we discursively refer to a more general framework known as *Dynamical Systems Theory* (DST). Since we wish to make this approach more known to a readership of music researchers, we will examine it without going into the details of its mathematical formulations. Having done so, we explore more specifically how the interaction of different performance dimensions (i.e., cultural, contextual, and personal) can give rise to continuous (re)configurations of constraints impacting on how music is generated and meaningfully enacted (see e.g., Loaiza, 2016), leading to a set of behavioural possibilities (a so-called *hypothesis space,* e.g., Jones et al., 2021). We then suggest that the body of the performer might be understood as the principal source of musical meaning-making (e.g., Davidson & Correia, 2001; Kozak, 2019; Reybrouck, 2020) as it plays a central role in establishing, regulating, and destabilising multiple live synergies within such a complex interplay of factors. Note that, besides being a source of inspiration, the body can also be experienced as a site of resistance. For example, Schroeder (2013) locates this resistance in the relation between the musician's body and the instrument (see also Auslander (2009) and Burrows (1987) on the instrument as a separate entity in tension with the musician).

In this article, we argue that bringing together conceptual tools from DST and *embodied cognition research* (e.g., Chemero, 2009; Gallagher, 2005, 2020) stimulates a cross-pollination of ideas and insights that can inspire novel investigations across a range of musical domains, including those interested in music education and development. This might contribute a new perspective to the ongoing debate on embodied music cognition – a topic that has hitherto focussed on bodily movements, kinetic awareness, and sensorimotor experience (e.g., Leman, 2016), leaving the broader theme of the dynamical interactions between the musicians and their world arguably less explored. As such, our preliminary investigation provides an apt counterpoint to such research and theory, extending previous findings in philosophy and cognitive science (e.g., Kelso, 1995; Thelen & Smith, 1994; Torrance & Frose, 2011) to the musical domain, with a specific focus on performance.

THE DYNAMICAL COMPLEXITY OF MUSIC PERFORMANCE

If we are to look at music performance as a complex system of interacting factors, DST can be a valuable ally. DST is a multi-disciplinary approach based in mathematics that models non-linear systems (Favela, 2020). Such systems cannot be described as a sum of independent components, as their variables are recursively related. Accordingly, the properties of a complex non-linear system cannot be reduced to its individual components, and the behaviour of its individual components does not completely determine how the system behaves and evolves as a whole. To understand these dynamics, DST employs difference-differential equations to model the feedback and feedforward effects of the non-linear, interdependent variables that characterize such systems, and to describe how various non-reducible properties emerge from phase transitions initiated across various temporal trajectories. DST has been employed in a variety of domains to examine how complex systems (from human beings to eco-systems) evolve over time (Juarrero, 1999; Thelen & Smith, 1994). As such, it offers a theoretical and empirical framework that can be applied to a range of music-related phenomena, including the ways musicians develop skills and creativity, communicate, and interact with each other, and adjust to perturbations in the musical environments in which they participate (e.g., Large, 2000; van der Schyff, et al., 2018).

For example, imagine how an ensemble performing the trio for violin, horn, and piano by György Ligeti would react to an unexpected noise coming from the audience. The whole trio may respond very differently if this disturbance occurs during the second movement ("Vivacissimo molto ritmico") or in the last one ("Lamento. Adagio"), giving rise to diverse adjustments and modes of engagement unfolding between musicians, and between musicians and this unexpected variable (i.e., the noise). Such adjustments illustrate that, from a dynamic perspective on music performance, the score – as a roadmap for performance – is open-ended to a certain extent, allowing the performer to flexibly and creatively interpret the music in relation to events in the environment. Or, in the words of Hegel (quoted in Benson, 2003), the performer may "compose in his interpretation, fill in what is missing [or needed]" to adequately respond to such events (see also further).

As this example is meant to illustrate, a constant negotiation of factors internal and external to the system can impact musical choices, opportunities, and outcomes in different ways. Inputs and constraints can be highly significant in determining musical products, shaping the evolving shifts and transformations of both the whole system as well as its sub-components (e.g., Mudd et al., 2019; Venhorst et al., 2018). It is important to note that such negations can be both conscious and unconscious. For example, the humidity of a concert hall (external factor) may lead to a clarinettist's unconscious adapting of the lip pressure. However, this might cause pain in the lips (internal factor) and the urge consciously to find a balance between acoustics and lip pressure, in view of producing the desired tone production.

The capacity to capture such aspects of human-music (or human-human) interaction mathematically – through a set of differential equations – makes DST particularly useful for empirical research interested in developing quantitative analyses of (music) performance. Indeed, recent empirical contributions in the field have increasingly embraced DST-inspired approaches to quantitatively model experimental work (e.g., Demos et al., 2014; Walton et al., 2014; 2017). That said, such a perspective also involves an arsenal of theoretical resources that can help researchers to describe a range of musical phenomena and behaviours from a systemic view, such as creativity, improvisation, or social participation (Borgo, 2022; Schiavio et al., 2021; van der Schyff et al., 2018). For instance, several contributions suggest that (musical) creativity is not fully realized by an individual (e.g., a composer or a performer), but instead involves a broader intersubjective and cultural grounding (Cook, 2018; Glăveanu, 2014; Linson & Clarke, 2017; Sawyer & De Zutter, 2009; Schiavio et al., 2020). This example illustrates how valuable new vistas on specific musical categories have been offered by research and theory that make use of various conceptual tools inherent in DST. As such, DST can provide a useful framework to examine how various interacting components can give rise to creative ideas or artifacts, also describing how they influence and shape each other. However, by looking at precise sets of phenomena, similar approaches might also run the risk of losing a more general view on what music performance entails. With this in mind, we suggest that a birds-eye view on music performance can provide complementary insights to those of existing accounts, inviting a constructive dialogue between those scholars interested in measurable musical and musical-related features (e.g., pitch, movements, etc.) and those enamoured by broader levels of description which cannot be fully captured quantitatively (e.g., musical experience) (e.g., Holmes & Holmes, 2013).

We argue that this latter research option can help us addresses the call to "*investigate music performance in its complexity*" issued by Fabian and colleagues (2015). A valuable attempt to explore this complexity has been put forward by Bourgeau (2006), who individuated three different general *dimensions* of music performance (see figure 1). The first one places the act of musical performance within a *broader context* – for example, culture in general (e.g., Western culture), and musical traditions (e.g., classical or jazz). The second dimension concerns the *specific situatio*n of a performance, namely the location and the atmosphere that arises during the musical event. The third one, instead, focusses on the *human dimension*, encompassing the appearances and behaviour of the specific individuals (performers and audience) involved in the performance.

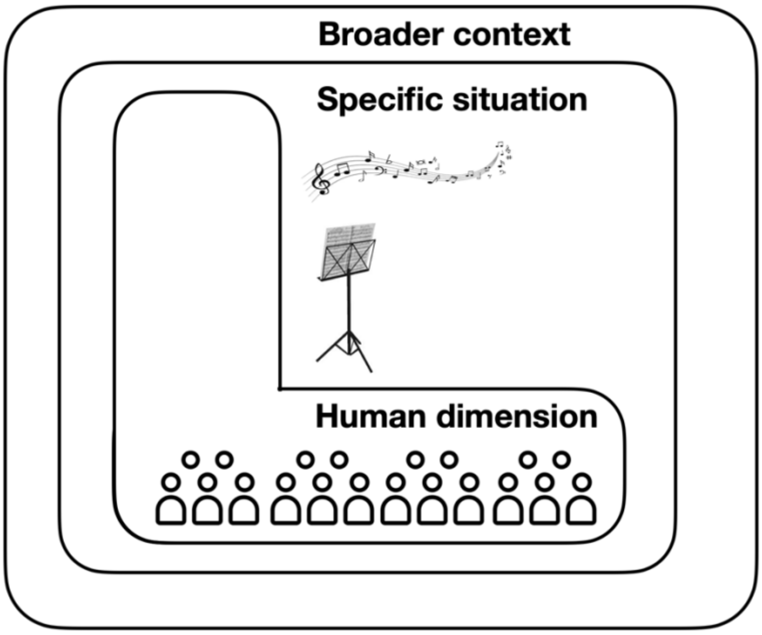

Figure 1. The components of a Western-based, music performance according to Bourgeau's dimensions.

The three dimensions that are depicted in figure 1 might be associated with relevant constraints, namely task constraints (e.g., performing a composition from a certain time period that asks for a specific interpretation), environmental constraints (e.g., the acoustics of the concert hall contribute to define the specific situation), and organismic constraints (e.g., the musician's ability to move their fingers reveals important nuances of the human dimension) (see Newell, 1986). Because the combination of these constraints determines the musician's action possibilities and choices in relation to the score in various ways, they can be understood to aid the musicians to endow the mere notated "skeleton" with "flesh and blood" (see Schonberg, 1992). That is, rather than bringing an exact mechanical reproduction of a prepared plan, as a musical software could do, the interaction of all these factors adds a living quality to the performance, thereby generating a captivating experience for both listener(s) and performer(s) (Chaffin et al., 2005; Lehmann & Ericsson, 1998). Live musical performance, by this view, becomes an open-ended meeting between the performer(s) and (the multiple constraints of) their surrounding physical, cultural, and social environment (Cook, 2013; Schiavio & De Jaegher, 2017; Reybrouck, 2012). As such, a performance unfolds based on a set of individual, performance or task, and environmental constraints (see also Newell, 2003).

Before we move on to explore such dynamics in more detail, we follow Chaffin and colleagues (2003) and suggest that the musical possibilities that these constraints offer are thought to shape the performance at four different *levels*, namely the basic, structural, interpretative, and expressive level (see also Chaffin & Logan, 2006). According to these authors, the *basic level* concerns familiar patterns, fingerings, and technical solutions necessary to perform the music; the *structural level* focuses on formal musical elements, such as section boundaries; the *interpretative level* refers to categories such as phrasing, dynamics, tempo, timbre, and how these can be modulated and, finally, the *expressive level* concerns the musical ideas the performer aims to emphasise and convey as the playing unfolds. Importantly, and differently from Chaffin and colleagues, we see the interpretative level as the performer's personal understanding of a musical work and the choices and decisions about how to convey musical meaning, and the expressive level as performer-controlled fluctuations in, for example, timing, dynamics, timbre, articulation, and intonation during the interpretation of a piece (e.g., Vuoskoski et al., 2014; see also Meissner, 2021). While it might be useful to separate such levels for the purpose of analysis, it should be clear that, in practice, changes in one level often describe changes at another level. For example, modulating the timbre of a certain pitch (expressive level), may require a different fingering solution (basic level). Figure 2 pictures how the different contextual, situational and human dimensions introduce a set of constraints that urge a musician to shape the performance at different levels.

Figure 2. Different contextual, situational, and human dimensions introduce a set of constraints that urge a musician to shape the performance at different levels. Note that this is an iterative and dynamic process.

It might thus be argued that any detailed analysis of the defining features of performance can only tell us little about the actual web of relationships, experiences, and possibilities that playing music entails. A dynamical perspective, instead, trades the focus on these single components to embrace complexity; as such, it explores musicking in terms of reciprocal loops and patterns of stability and instability emerging across multiple factors. Figure 2 summarizes the discussion so far, bringing together the dimensions, constraints, and levels we have introduced above.

Stability, instability, and change

Emil Gilels, one of the most famous classical pianists of the 20th century, once described the dynamical character of a performance as follows: *"it is different each time I play, and it is a process which [...] includes mastery of the work, knowing the details, being comfortable with it, and then adding the fantasy"* (quoted in Mach, 1991, p.123). This excerpt aligns well with a case study by Chaffin and colleagues (2005), which showed how playing the same piece over different performances gives rise to different experiences. Even when the same scores are involved, music performance cannot be seen as a static activity; rather, it always involves a negotiation of different factors and meanings, where the reciprocal interaction of stability (e.g., the score) and change (e.g., adaptations based on the musical environment) takes the lead and defines the trajectory of the system and its sub-components (Barret, 2014).

Interestingly, the stability of a system and the way it changes can be examined from a *macro* and a *micro* level (e.g., Hammarberg, 2017). In a musical context, the former is concerned with how different performances of the same musical piece might develop over time. This is a well-known phenomenon for a musician – one that is often denoted as maturation. Yet, performances by the same interpreter often show good levels of consistency, allowing a listener to recognize "the signature" of a performer (Repp & Knoblich, 2004). The micro level, conversely, refers to how a specific musical piece unfolds within the timeframe of its performance. With the language of DST, it might be helpful to characterize music performance (like many other phenomena occurring in time), as a series of moment-to-moment events, each characterized by a certain *state.* In this light, a performance can be conceived of as a constantly developing trajectory, passing through a set of possible states – a so-called *state space* (Juarrero, 1999). Accordingly, the more possible states (with their sets of variables) there are, the more complex the system is. Such possible states are co-determined by the dimensions of music performance we mentioned earlier: not only does a particular musical event (e.g., how a certain chord is realized) depend on the properties of the piece itself (e.g., its style); it also depends on the contextual situation (e.g., the acoustics of a concert hall), and on a rich variety of human factors (e.g., the emotional state of the performer), among others. The variables concern the technical, structural, interpretative, and expressive levels of a performance as described earlier (Chaffin, et al., 2003; Chaffin & Logan, 2006).

To better explore how a music performance can be understood as a trajectory through a state space, we now refer to the notion of *attractors* and *basin of attraction* (see figure 3 for an example of trajectories in the state space).

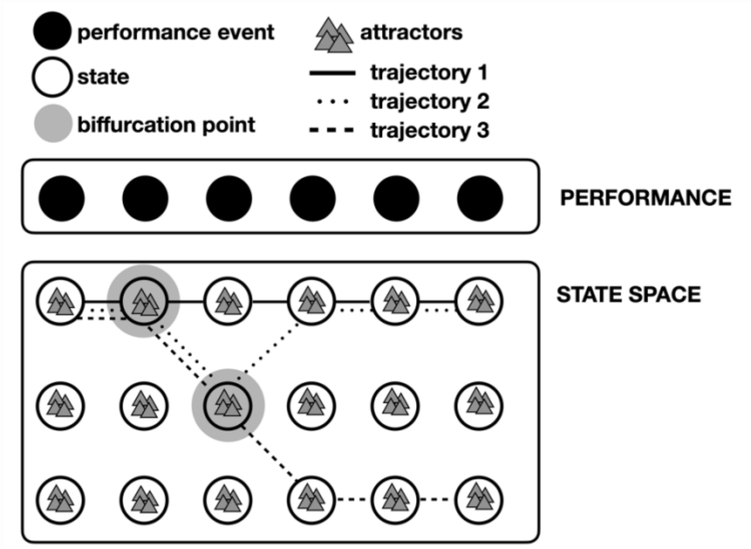

Figure 3. Schematic representation of different trajectories in the state space. The bifurcation points allow to steer a trajectory in a new direction.

Attractors are points in the state space that, by embodying the set of constraints at the different levels of a performance, have a greater than average probability of being part of the system's developing trajectory in time, thereby shaping the stability of the system (Juarrero, 1999). In the context of musical performance, they may be innate reflexes or learnt behavioural patterns, representing a state of minimum energy (i.e., not requiring effort) that is resistant to perturbing influences. From this point of view, we can consider how some elements of a piece of music are more strongly predetermined than others, guaranteeing its stability: a task-constraint determined by a certain stylistic convention, for example, can impose specific modes of articulation of the notes, increasing the likelihood that a musical passage will be performed with a phrasing of one type and not another (e.g., detaching notes vs slurring). However, other musical elements maybe be less fixed in advance, and can therefore be interpreted in different ways: a musical scale, for instance, can be played with a range of diverse articulations (completely slurred, alternating slurred and detached notes, etc.), depending on many factors. These may include the contextual dimension (e.g., playing it for an exam in front of judges, or while improvising alone), or the kind of atmosphere the performer wants to create.

Attractors also have a *basin of attraction*, containing a set of initial states that converge on the attractor (Palermos, 2016). Accordingly, the basin of attraction determines the degree of possible deviance from the attractor, without being drawn to another possible attractor. It is only through significant perturbations – or *bifurcations* (critical instability thresholds) – that a performance's trajectory can be changed, with its state being pulled into another basin of attraction (see Figure 4). In music performance one can think of such bifurcations as elicited by, among other things, a technical problem (e.g., an unresponsive key), the audience's reaction (e.g., seeming bored), an unexpected initiative of a co-player (e.g., a different articulation or dynamic). Such situations – which may lead to a consciously experienced breakdown in the performance experience (see also Winograd & Flores, 1986) – might give rise to new attractors. Note that in this regard, an attractor in one task can be a *repeller* in another task. For example, the attractor of slurring two notes in Brahms might be understood as a repeller in Mozart, because of stylistic conventions. See figure 4 for a summary of how the shaping of a performance from dimensions to levels is related to a set of attractors, or points in the state space towards which a performer is drawn.

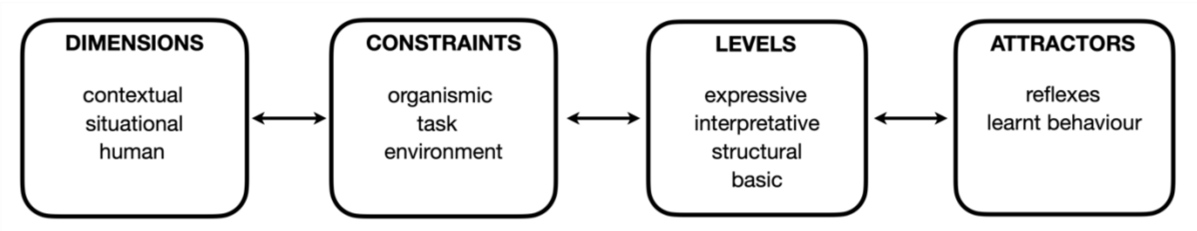

Figure 4. The shaping of a performance from dimensions to levels is related to a set of attractors, or points in the state space towards which a performer is drawn.

Because music performance always involves more than just one attractor, performances might be said to occur at *the edge of instability*. This means that, if we want to keep our musical activity valuable, coherent, and meaningful, it is necessary to maintain a certain balance in the system's readiness to transit between multiple attractors (see Bruineberg & Rietveld, 2014). Here, the concept of *metastability* is of interest. Put simply, metastability defines the spontaneous alternation between possible states exhibited by a complex system. This involves a tendency toward an optimal self-world attunement, which allows for a context-sensitive openness. Musical expressivity might be a good example: according to Landes (2013), expressivity might be best understood as a "metastable equilibrium" or a "precariously stable" state that is endlessly reconfigured by new factors emerging within the performance. As such, expressivity can be thought to comprise a "trajectory of metastable equilibriums". In our view, such a metastable state can be described in terms of the "expressive moment" advocated by Leman (2016) – a notion meant to capture how a musician generates new expressive nuances due to a push-and-pull process occurring between their performance plan and the moment-to-moment contingencies at the heart of a specific performance situation (see also Nijs, 2017).

The continuous interplay of stabilizing and destabilizing occurrences is not only an important aspect of expressive performance, but also a condition of possibility for meaningful music-making more generally – including its creative properties. Indeed, the musician's openness and responsiveness to bifurcations allow a performance to be shaped "on the spot" with little or even without pre-planning (see also Schiavio & Kimmel, 2021). This capacity might let the musician fluidly discover, refine, and consolidate opportunities for musical thought and action as they creatively navigate the musical territories between different attractors, and attractor basins, forming, in turn, adaptable self-environment couplings that may increase or decrease stability (Juarrero, 1999; van der Schyff et al., 2018; van der Schyff & Schiavio, 2022). The range of behaviours of the system and its components can produce states and configurations that either stabilize or destabilize the evolving network (Favela, 2020), bringing up new perspectives and views as well as new musical challenges. As such, categories like functionality, structure and information are being constantly negotiated across various levels and timescales, as we saw when describing the various aspects of Western music performance from a general viewpoint (see again Figure 4). Note that musicians may intentionally introduce instability to prompt a state shift and, as such, open new ways of performing. For instance, the relationalities established by musicians can uncover new avenues for action that may necessitate innovative methods of performance. This can reveal both conscious and unconscious modes of interaction with the musical environment created in their real-time actions.

Starting from its main dimensions and sets of constraints, we have explored the idea of defining performance as sets of trajectories emerging through a state space. The reciprocal development of these trajectories gravitates around stability and instability, where the former relates to attractors, and attractor basins, and the latter to bifurcations. In the next section, we go deeper into the nature of their complex interaction.

The interaction between sub-systems

Most components of a musical performance can be conceived of as dynamical systems on their own. These include musicians and audiences (e.g., Bissacco and Soatto, 2009), as well as the musical instruments being played (see e.g., Fletcher, 1999), and the music being performed (see e.g., Crowe, 2004; McIntyre et al., 1983). The score takes a somewhat peculiar place because no feedback loop exists between performer and (traditional) scores (see Palermos, 2014). That said, it should be noted that a large part of the Western music repertoire remains surprisingly indeterminate in nature (Bazzana, 1998). Such an insight arguably makes the musical score a “constant stock of possibilities” (Benson, 2003; see also Cook, 2013; 2018), allowing a musician to “*compose in his interpretation, fill in what is missing, deepen what is superficial, ensoul what is soulless and [...] appear as plainly independent and productive*” (Hegel, 1975).

We define this space for musical interpretation as a “hypothesis space” (more on this later). Consider how an unexpected expressive nuance developed by a musician on the spot may violate a given “hypothesis” about the piece, creating a sense of surprise that could destabilise the overall performative or listening experience. This introduces a precariously stable state that allows for novel interpretative and expressive adaptations to the prepared plan to emerge. For example, think of a situation where a cellist in a string quartet intentionally introduces a rhythmic phrase at a faster tempo than usual to initiate more excitement in the music. This unexpected shift may temporarily destabilise some members of the group who then jointly adapt their parts to negotiate the new tempo. The musical qualities that arise from this process, although initiated by the cellist, involve all the musicians in dynamic interaction. Again, we stress that such emerging nuances are not independent of the complex web of relationalities of which a performance is made. In fact, differently involved dynamical systems engage in a continuous non-linear interaction, stemming from the cooperative or inhibitory feedback loops between the interacting parts (Palermos, 2014).

When looking at such dynamics in more detail, we could distinguish between *structural* and *functional* aspects. In a musical performance, structural aspects might concern the patterns of communication unfolding between various (sub)systems. Examples might include the physical connections established by musicians with their instrument (see Nijs, 2017), or the embodied, physical interaction that links listeners and performers with music (see Leman, 2007; Kozak, 2019). Functional aspects, conversely, concern the laws that shape the action and co-evolution of the diverse factors being involved in the description of the system (Stankovski et al., 2017). For example, we could consider how the quality of the musician-instrument interaction is determined by the process of instrumentalization, that is, the emergence and evolution of artifact components that shape a musical instrument contextually (Nijs et al., 2013).

Another interesting aspect of the coupling between components of a system is their description in terms of *strength* and *directionality* (Stankovski et al., 2017). The *strength* concerns the information flow between coupled elements, in particular the gain that reinforces the coupling (Gushchin et al., 2016). Although the stability of a system depends on the strength of the coupling and is therefore often conceived of as a constant, the coupling strength between two systems can also be dynamic. Think again of the coupling between a musician and their instrument: the more optimal the relationship (and thus the strength of the coupling), the less the coupling is prone to bifurcations. Note that this might be genre-related (see also Dogantan-Dack, 2022). For example, classical musicians might agree with such perspective (e.g., Simoens & Tervaniem, 2013), while pop/rock, jazz or experimental musicians may see it differently (see also for example the work of Auslander, 2003; Schroeder, 2005; Rebelo; 2006). The *directionality* concerns the direction of influence, namely the direction of the stronger coupling. For example, in case of the musician-instrument relationship, the impact of the instrument on a musician's body can be seen as the direction "instrument to musician". Instead, successfully controlling the instrument in the service of one's musical intentions can be seen as the direction "musician to instrument" (although there will always be a feedback-feedforward flow that the performer must engage with).

Clearly, the strength and directionality of the different couplings nested within music performance can play a major role in determining how its different trajectories diverge and converge. This, in turn, exerts an important influence on the range of conscious *actions* and unconscious *operations* a musician relies on in their activity (Nijs et al., 2013). Consider, for instance, how an expert musician may switch their attention toward a particular fingering that was always taken for granted. Perhaps the musical result was already satisfactory, so no particular focus was needed. However, by concentrating on this fingering solution during performance, the musician realises that a more expressive possibility can be developed with a simple change. Through the lens of DST, such an attentional switch might be considered a change within the behavioural basin (in case only this fingering changes) or even a qualitative change (bifurcation) in the behaviour of a dynamical system in case it leads to a chain of different fingerings.

Bifurcations may have a variety of causes, as they could emerge from different couplings. For example, a sudden thought (e.g., "Oh, our violinist changed phrasing") during performance may cause a breakdown in the musical flow, altering the structure of the performance in various ways (e.g., change of phrasing too). As we saw, the strength of a coupling determines the stability of the system and the degree to which it is sensitive to bifurcations. And while some changes in performance may be brought forth in an unconscious way, others might necessitate a more conscious processing. This brings the discussion to the role of the musician's body in music-making, a topic that has been at the heart of recent scholarship in interdisciplinary musicology for the last decades (Cox, 2016; Davidson & Correia, 2001; De Souza, 2017; Godøy, 2003; Leman, 2007; Reybrouck, 2006; van der Schyff et al., 2022). We suggest that the body of a musician is vital in the negotiation of the various constraints shaping performance; to manipulate different factors and their patterns of convergence and divergence; to establish and refine couplings that may give rise to novel trajectories or disrupt existing ones; and, in all, to ensure a coherent, meaningful interaction of the different components and subsystems at the heart music performance. By coherent, we mean that a performance feels coherent when striking the right balance between instability and stability, and "sensing" all the different relationalities that are formed and transformed through performance. In the following section, we discuss the fundamental role of the body in music performance and elaborate on enactment and the coping processes that allow a performer to deal with the complexity of music performance.

Hypotheses and affordance competition

The reciprocal interactions between the different coupled sub-systems and the way they shape the global unfolding of the performance, generates a complex situation in the middle of which a musician must make sense of all the information that emerges from these interactions. How can the musician engage with this evolving network of trajectories, factors, and attractive forces? An important resource to do this is the skillset a musician has developed through their learning experiences. This includes the ability to optimize the calibration of movements and action with the instrument in both conscious and unconscious situations – an ability that also depends on the successful integration of the various (affective, social, etc.) factors inherent in performing music. In other words, it is suggested that the body takes on a major role in bringing together, regulating, and governing the set of trajectories reflecting the dimensions and constraints of a musical performance.

While during deliberate practice many musical decisions can be taken to determine a plan for the performance at the different levels (basic, structural, interpretative, expressive), it is well-known that contextual demands and contingencies during performance might alter the pre-defined performance plan, with changes affecting both local and global dynamics (Schiavio & Høffding, 2015; Nijs, 2017). As such, musicians need to remain open to salient "actionable" elements, or *affordances,* that present themselves unmediated and invite skilled responses (Gibson, 1979; Krueger, 2014; Nijs, 2017). This trades the focus on planned musical behaviours for a more flexible understanding of music performance – one that is rooted in a real-time attunement to the emerging action-possibilities. Here different (behavioural, affective, communicative, etc.) trajectories can be adaptively regulated in a context-sensitive fashion as the performance unfolds. In the process, the musician must select and act upon specific affordances, forming multiple (possibly competing) *hypotheses* concerning their roles for the stability (or instability) of the system, as well as their overall artistic consequences (see Pezzulo & Cisek, 2016).

Basically, a hypothesis is a model of what causes certain sensory input (Hohwy, 2010; see also Donnarumma et al., 2017). This means that, when musicians perform a certain action, they expect a certain result. For example, a certain way of bowing (e.g., sul tasto), causes a certain sound quality (airy, flute-like effect and warmer sound). It should be noted that while alternative hypotheses can be formulated serially (i.e., from one performance to another), they can also be developed during the ongoing (musical) activity (see Cutietta, 1984; Pezzulo & Cisek, 2016). This makes music performance a constantly evolving space where different performance possibilities or "hypotheses" can be put forward and explored in the spur of the moment. For example, a trumpeter playing a classical piece of music, such as Haydn, may have different possibilities for slurring or detaching notes in a certain passage. Note that, while this can be read as a linear process, this is not the case in practice. Music performance happens in the moment and involves a range of interacting dimensions including bodies, instruments, musical-stylistic constraints, acoustic spaces, etc. By this view, such a "hypothesis space" describes the range of affordances (musical possibilities, interpretations, etc.) a musician might act upon. As depicted in figure 5, each hypothesis might be thought to define a specific trajectory through the state space, embodying specific patterns of behaviour.

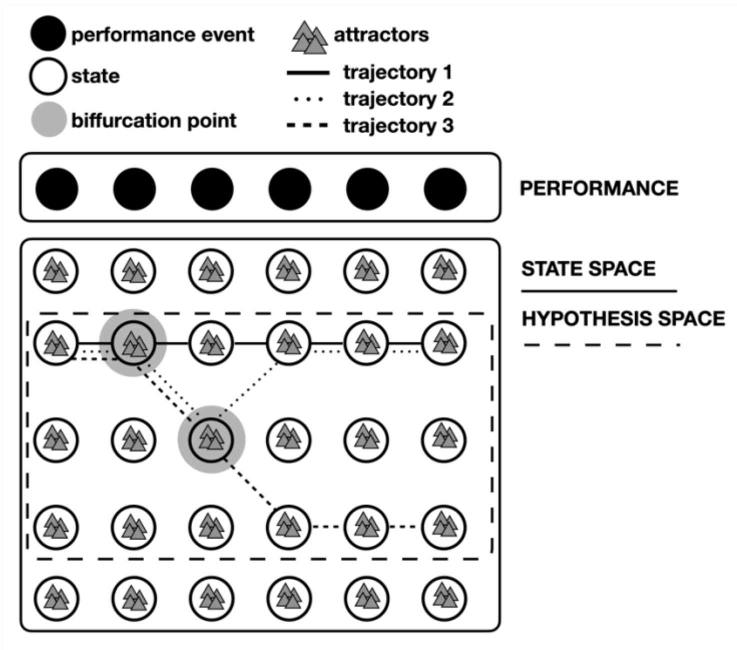

Figure 5. The state space contains a hypothesis space that encompasses different hypotheses or 'interpretations' of the music.

To offer a more vivid look at this hypothesis space, it might be helpful to think of a generative model where certain hypotheses are more likely to be prioritized than others (Pezzulo et al., 2017). This model, developed through practice and experience, but also on the basis of knowledge of, for example, a musical style, determines which hypothesis is most suited for a specific musical outcome. For instance, interpretations of baroque music in recent times are significantly less open to freedom in timing and dynamics, and musicians might need to recalibrate their intentions as they select the "winning hypothesis", that is, the one with the higher posterior probability (see also Cisek, 2007; Kirchhoff, 2018). Importantly, such hypotheses may not be only generated through conscious reflection as in the example of baroque music; instead, they can develop within the concrete dynamics of musicking as they encompass exteroceptive (i.e., auditory, visual), interoceptive (i.e., visceral), as well as proprioceptive (i.e., motor) information.

In music performance activities there is often a preferred hypothesis from the start, toward which many trajectories tend to be directed. This hypothesis is the result of the musician's deliberate practice. As such, it might be argued that a generative model helps one navigating the hypothesis space, shaping how actions and affordances produce live synergies associated with different properties of the musical event. For instance, to test the hypothesis that placing the right hand closer to the sound hole of the guitar when playing a piece from the romantic repertoire (e.g., Grand Sonata in A major by Paganini) might increase expressivity, a performer could allocate attention to a range of salient ecological factors, trying to corroborate the prediction being made (Wiese & Metzinger, 2017). Salience is defined as the information gain based upon the expected resolution of uncertainty about explanations for sensory input (Donnarumma et al., 2017). However, as the generative model is characterized by a set of expectations based on musically relevant action-perception couplings, the musician's body ultimately plays an important role in testing the hypothesis, as it accumulates evidence through experience. For instance, while the guitarist may explore different right-hand solutions in precise moments of the piece, the expert harpsichordist might realize that their recent interpretations of Benedetto Marcello's Sonatas did not provide an adequate response from the audience, whose expectations – so the story goes – might lean toward a more philologically-oriented rendition. In both cases, the body of the musician can generate immediate adjustments that could re-orient the musical trajectory being developed. Indeed, musicians can get an *optimal grip* on the performance by selectively responding to available affordances (Bruineberg & Rietveld, 2014; Bruineberg et al., 2018) and transforming in turn the relationships between various musical factors via perceptually guided actions (Varela et al., 1991).

Note that affordances do not present themselves as independent, *a priori* possibilities for action, but rather disclose themselves as nested structures that only make sense contextually (Bruineberg & Rietveld, 2014) – a characteristic that in music performance is facilitated by the musician's "big picture" of the music (Chaffin et al., 2003). For this reason, affordances might be understood to change over time due to events in the environment and the performer's own actions (Pezzulo & Cisek, 2016; Rietveld & Kieverstein, 2014). This resonates with the definition of affordances by Stoffregen (2003) who describes them as "opportunities for action; […] properties of the animal–environment system that determine what can be done" (see also Chemero, 2003). By this view, the musician's body has a privileged access to the full spectrum of performance levels, from technical execution (e.g., the use of different fingerings to alter the timbre) to expressivity (e.g., exploring different timings to emphasize a certain harmonic progression) in response to or anticipation of particularly structures of affordances (e.g., the audience expectations). This also implies that not all affordances are equally relevant: already available affordances can be complemented by newly (un)intentionally created affordances, which can then be engaged with to perform actions with the function of achieving other goals. As such, a process of affordance competition emerges. That is, once several affordances or "desirable actions currently available in its environment" are specified, the invited actions are weighted in terms of their outcomes (Pezzulo & Cisek, 2016, p. 415). Because affordances can compete at different hierarchical levels (Pezzulo & Cisek, 2016), affordance competition entails a hierarchy of control loops that involves top-down and bottom-up signals (Cisek, 2012). The higher levels might encode more abstract goals (e.g., playing expressively) at the same time creating expectations for the lower levels. And what happens at lower levels (e.g., how to solve a specific technical difficulty) may provoke changes at higher levels (e.g., affecting expressivity).

In the next section, we provide a more general view of the role of the body in performance by bringing together the insights developed so far with the principles of the school of thought known as *embodied music cognition*.

Integrating a DST and an embodied music cognition perspective

Recent research and theory in interdisciplinary musicology have crucially emphasized the role played by the body in shaping musical experience, from performance to listening (Gritten & King, 2011; Iyer, 2002; 2004; Juntunen & Westerlund, 2001; Lesaffre et al., 2017; Moran, 2014; Molnar-Szakacs & Overy, 2006). Within this research landscape, the emergence of new technologies such as motion capture devices and muscle sensors allowed the systematic measurement of musicians' bodily involvement in music performance. Accordingly, a large body of studies has focused on the gestural dimension of music-making, exploring the links between movement and categories such as expressivity, meaning, or communication (Borgo, 2005; Leman, 2007; 2016). Here, musical intentions are thought to be reflected in the musicians' overt movements. As such, these can be associated to target notes in certain musical phrases (see e.g., Desmet et al., 2012; Shoda & Adachi, 2012; Thompson & Luck, 2012), or to degrees of expressiveness of bodily motion (Davidson, 2012; Wanderley, et al., 2005) among others. This research is fascinating but, as these examples are meant to illustrate, it often remains too focused on the quantifiable properties of the musicians' movements and their sonic outcomes, perhaps losing a more general viewpoint on music performance.

To offer a complementary view that starts from a broader perspective and that embraces complexity and dynamicity, we follow the insights recently developed by Leman (2016) when discussing what he labels as an "enactment process" – an active bodily involvement with music, whereby a sound-movement-intention connection is established and brought forth in the daylight of musical experience. It is argued that patterns inherent to sounds (e.g., a chord sequence or a melody) are associated with movements (e.g., defining certain shapes, directions, and energy), and to the musician's artistic intentions and personal states (e.g., emphasizing a specific emotion), leading to novel forms of musical meaning-making.

From such a perspective, the body may be considered as the primary sphere in which all significance is initially engendered (Merleau-Ponty, 1945; Sheets-Johnstone, 1999; 2010; 2012). The animated body creates space for action made of gestural, perceptual, social, and creative possibilities, where acquired skills and lived experience govern how we address the shifting demands of the musical environment we encounter in the process. By this view, it becomes possible to *bodily attune* to the music and rely on our body to generate and transform meaning within the concrete dynamics of music making.

Leman (2016) argues that different bodily processes underlie this form of musical sense-making. First, he individuates three mechanisms at the heart of the latter in prediction, entrainment, and alignment. *Prediction*, sensing what comes next in the music, is based on sensorimotor schemes that, originating in a repertoire of acquired actions (e.g., through deliberate practising) and possibly innate reflexes (e.g., postural or stretch reflexes), realise tight couplings between motor commands and expectations (Pezzulo, 2011). They involve kinaesthetic, tactile, and haptic sensing particularities related to the biomechanics of the body itself (e.g., the length and shape of our legs and arms; see Dahl et al., 2014) and to diverse bodily states (e.g., feeling fatigued or being energetic). It is assumed that these particularities have an impact on the predictive processes and therefore influence anticipation of expected outcomes. *Entrainment,* very generally described as the process of in which two or more biological or mechanical systems interact with each other (Clayton, 2012) or a form of interaction that 'propels human rhythm to synchronize with musical rhythm' (Leman, 2016, p. 99)*,* is known to be also determined by natural motor variability (i.e., it is shaped by prediction and adaptation processes; e.g., Demos et al., 2014), motor resonance and preferred tempo (i.e., it is determined by biomechanics of the body and neuronal clocks; e.g., Leman 2016, p. 105), and body movement (e.g., by guiding attention; e.g., Fortuna & Nijs, 2022). Leman, finally, relates *alignment* – the ability to feel the music and to align one's movements to it – to the natural music-movement correlation that many people can feel. It is suggested that, alongside the observable movement patterns, it also involves bodily states associated with effort and arousal and known through proprioceptive observation. Two types of alignment are distinguished here: phase alignment (the synchronization of movements to salient time markers in music), and inter-phase alignment (the way the continuous expressive flow of physical actions matches the time in between the beats of the music).

Second, the musical enactment described in the work of Leman (2016) can be further explored considering the processes of hypothesis generation and affordances navigation we have illustrated in the previous section. Arguably, such processes are mostly associated to alignment, whereas entrainment and prediction might be seen as the facilitating conditions of both phase and inter-phase alignment (Leman, 2016). When entrainment and prediction run smoothly, indeed, performers can freely navigate the shifting landscape of affordances; consider different hypotheses based on the coming sensory signals as well as their own predictions; and cope with them to generate new meanings in the spur of the moment. So, when things do not go smoothly, performers experience moments of uncomfortable instability and must engage with the extended musical environment to maintain or regain coherence and communication, making rapid in-the-moment decisions that influence and are influenced by the unfolding musical environment. Here, we can appreciate the role of the body in this enactment process: musical choices ultimately emerge from rolling patterns of action and perception that modulate the *effectivities* (Hirose, 2002) of the affordances, developing live synergies (i.e., between the performer and the musical instrument, the audience, the co-players, the physical environment, etc.) that shape the musical outcome.

With this in mind, we may consider again the musician-instrument coupling: this is based on an *incorporation* of the instrument, which requires the transformation of the latter from a mere material artefact or tool to a *functional organ* – one that constitutes an integrated web of resources for musical action (Kaptelinin, 1996; Nijs et al., 2013). As such, the instrument's use and functioning become so natural that it may be perceived as an organic component of the musician's body (Nijs et al., 2012; 2013; Nijs, 2017). Consequently, instrumental gestures might be seen to become constituents of the musician's body schema (Jensenius et al., 2010), and, as such, part of the somatic know-how of the musician (Behnke, 1989). In this way, the instrument becomes a component of the latter's cognitive ecology, taking part in the musical enactment processes described above (Riva, 2009; Riva, et al., 2004). This means that not only do novel affordances emerge as the musician interacts with their instrument; the instrument can also be seen as an extended bodily resource that helps navigate the field of affordances through a flexible, coordinated, skill-based acting (Pezzulo & Cizek, 2016; Rasmussen, 1983; Shoebridge et al., 2017). This last example is meant to illustrate how the musical body plays a key role in developing coherent self-world couplings at the heart of music performance: the body actively seeks for and generates novel resources to explore and respond to specific environmental perturbations at the crossroads of stability and instability; it contributes to transforming various physical (e.g., acoustical), personal (e.g., emotional), and ecological (e.g., social) factors by integrating action and perception; and it constantly establishes, modifies, or disrupts trajectories across the dimensions, constraints and levels of a musical performance. In all, the body brings forth an integration of factors inherent to sound, action, experience, and intentions, ensuring the coherent development of the "enactment processes" from which musical performance flourishes (Leman, 2016).

CONCLUSIONS

In this article, we have explored the complexity of music performance from a theoretical standpoint, integrating conceptual tools from DST and embodied music cognition research. In particular, we have considered how an understanding of music performance as a complex system of interacting components may help us clarify how different interpretative "hypotheses" are generated and selected with little or no pre-planning. Our take is that the moment-to-moment contingencies of performing music involve live synergies between the musician and said different (physical, ecological, emotional, etc.) components, whereby a balance between stability and instability is actively sought. To do this, one needs to remain open to the range of possibilities offered by multiplicity of affordances, which develop as the music unfolds across the range of trajectories of related subsystems. In examining such a dynamical self-world interplay through the lens of what Leman (2016) refers to as an "enactment process", we have placed considerable emphasis on the role of the body – conceived of as the general driver of musical sense-making. Here, we noted how the coupling between musician and instrument can be understood as optimal when it does not interfere with this process, but instead produces additional resources for navigating the hypothesis space (Nijs et al., 2013; Nijs, 2017; Simoens & Tervaniemi, 2013).

Our approach complements existing theories in the musicological research landscape when it seeks to overcome inherent dualities between interpreters, musical instruments, ecological constraints, personal factors, and the music itself. A model of music performance shaped on DST examines all such elements in their reciprocal interplay, without posing a linear input-output scheme to capture their causal web of mutual influence. Instead, they can be seen as an individual, structured system involving divergent and convergent patterns, trajectories, and forces. Additionally, categories like movement, expressivity, emotion, or intention in musical performance, appear to be more related to the musician-instrument coupling than previously thought: the musical instrument is not a neutral tool, nor is the body a reifiable piece of the world that functions as an input-output controller; rather, body and instrument merge into one unique entity that actualises sound-movement-intention connections as it negotiates between competing "hypotheses".

The embodied flavour of this approach can be also appreciated when similar insights are applied to areas such as music education and development (Schiavio & van der Schyff, 2018). Within the European classical music educational tradition, instrumental music learning has been based on practices that were passed down for generations from teachers to students (Burnard, 2014). Today, this so-called *Conservatory tradition* prevails worldwide (Jorgensen, 2011). Despite its achievements, such as high standards of music performance, brilliant musicians, and outstanding instructional materials, this tradition – and especially the underlying master-apprentice model it entails – has been heavily criticised (Bransford, 2000; Washburn, 2010). Studies have suggested that this model is often characterized by a teacher-centred approach with a focus on technique in function of reproductive imitation, often corrected by verbal feedback and aural modelling, thereby neglecting important aspects of learning involving learner's autonomy, self-efficacy, and self-regulation (McPherson & Welch, 2012).

In our view, a DST-inspired approach integrated with the theoretical resources of embodied music cognition might provide the foundation for a stronger pedagogical and musicological framework – one that acknowledges the complexity of music-making in a refreshing way; that offers novel tools to examine the body-in-action and its pre-reflective properties in artistic contexts; and that might reveal fascinating ways in which musician and instrument merge together as one (Nijs et al., 2013; Nijs, 2017). Because such insights speak to both music performance and education, we expect future research to apply a DST-embodied approach to the latter area as well (Bremmer & Nijs, 2020, 2022). This can complement the preliminary framework on music performance we develop here and help explore new practical possibilities for learning. This might involve introducing an approach where experimentation/exploration and improvisation can develop in close interaction with score-based playing since the very first musical steps of one's musical journey. For example, teachers can promote the use of expressive body movement to help students navigate the broad landscape of musical affordances via improvisation, exploring in turn different competing "hypothesis" and fostering musical understanding, expressiveness, and creativity (Nijs, 2019). Another example is the use of drawing to music, trying to find different ways of visually representing the music as a means of exploring the musical affordance landscape (Fortuna & Nijs, 2021, 2022). As such, learners can autonomously construct meaning in the music they play (e.g., Han, 2016).

In all, we believe that introducing a DST-informed perspective enriched by an embodied music cognition approach on music performance can help researchers, theorists, and educators disentangle the cognitive-motivational architecture at the heart of musicking, individuate the key factors involved in this phenomenon, offer a novel view on the instrument-musician coupling, and promote models and interventions aimed at re-enforcing musical skills and improving creativity. As such, it has a strong potential to steer the development of future research and practice.

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