Multiscale approaches to music and the embodied brain

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Abstract.

A wide body of research is currently being devoted to investigating the multiscale processes across the brain and body, and the nature of their interactions. The purpose of this paper is to supplement these analyses of brain and body dynamics by paying particular attention to the multiscale organisations also found in music, and ways in which these systems interact. We proceed in identifying scaling laws as a signature for multiscale features of a system and make the methodological choice of distinguishing scale free structure from scale free dynamics. We follow these distinctions in demonstrating how specifically (i) hierarchical temporal structures, (ii) long-range temporal correlations, and (iii) musical information as scale free structures, relate to activity in the brain and body at various temporal or spatial scales during music perception and performance. Further, this is paralleled in the in the following scale free dynamics of choice, namely, (iv) resonance and entrainment, (v) power law distributions, and (vi) 1/f scaling. Though the ubiquitous scaling relations across musical activities, performance and music itself touch on the theme of universality, we outline how differing theoretical proposals arise in such contexts. Using these examples, we identify their overlap and divergence, and propose future directions for inquiry along these lines.

MULTISCALE APPROACHES TO MUSIC AND THE EMBODIED BRAIN

1. Introduction

Multiscale systems span the complex interrelation between brain and body in order to meet the adaptive challenges demanded from significant environmental and physiological factors [1, 2]. Formulations of order in the face of environmental constraints and perturbations through scaling laws, recurring dynamic regularities that can be shown to underlie widely different mechanisms at different spatial and temporal scales, may serve as one such way of meeting these challenges and enabling adaptive behaviour [3, 4]. Investigations into these ordered mechanisms have been well studied in physics, chemistry and biology, but such methods have shifted towards the cognitive sciences in recent decades [5, 6, 7]. This shift has provided significant insight into scale free mechanisms that span perceptual [8], motor [9], and social systems [10].

In this review, we intend to contribute to this shift using the domain of music cognition as a paradigmatic example and demonstrate music as a multiscale phenomenon, thereby making use of music and performance as a medium for understanding the multiscale relations between the brain and body. Said differently, this review intends to draw from the research domains of music cognition and performance to highlight in what ways various scaling mechanisms are essential to, and often characterise [11], musical activities, ranging from listening, moving, and experiencing.

We begin by outlining what is meant by multiscale systems in neuroscience and music, and how this is directly related to brain-body relationships in music specific contexts, in doing so distinguish scaling structures from scaling dynamics. Then we will highlight specific examples of such systems at work during musical activities across scales from brain, body, to groups. Finally, potential insights from methods of multiscale neuroscience will be emphasised and how this can inform music cognition and embodied cognition more generally.

2. “Multiscale”, Neuroscience, and Music

For a phenomenon to be considered ‘multiscale’ is for there to be dynamic regularities which can be studied as nested, interrelated structures at different scales or across varying periods of time. One way of specifying something as multiscale is through identifying scaling laws as a relation across these multiple scales as scaling laws are a useful heuristic for determining essential and nonessential features of the interacting components of complex systems [12]. A succinct definition for the presence of scaling laws can be provided as; “An abstract object is scale invariant or scale free if relevant features of the object remain invariant under dilations of the object along a set of dimensions, such as space, time, node degree, distance etc.” [13], p.3. Put more simply, scaling phenomena are events at different scales that show topological or statistical self-similarity and statistical dependence on the measurement apparatus [14], and it has been insisted elsewhere that it is only in virtue of such scaling laws that a system can be said to be self-organising [5]. This is not to say that there is an indefinite limit to the proportional relation between a variable and its scaling exponent, physical conditions regularly determine constraints to which an object can be scaled, rather there are necessary upper or lower bounds to which some scaling mechanisms can be studied. For example, 1/f scaling offers a well-specified relation between phenomena in multiscale systems through specifying an exact exponent which at once details how one scale relates, or traverses, to another and how a system can be said to display self-similarity across time and frequency domains. 1/f scaling is a popular mechanism to demonstrate scale invariance in a multiscale system, but is by no means the only relation and we shall outline further examples.

Implicit in this definition is the theoretical concept of ‘emergence’ which has found increasing use in science and philosophy of science as an ontological concept or as a mode of explanation[1]. There are important concerns to do with distinguishing forms of emergence as strong or weak, the scope of these strong and weak distinctions, and reducibility, although we wish to make use of the concept insofar as it pertains to *universality*, specifically the universality of scaling laws across brain and behaviour relations in music [15]. It is these universal scaling relations that are the focus of this paper in signifying multiscale phenomena in musical contexts. While we have established what is meant by ‘multiscale’ and will proceed in identifying specific universal scaling relations that characterise self-similar activity, we must first sketch how a multiscale approach or framing can be taken towards neuroscience, making explicit how this framing follows from the definition of ‘multiscale’ we have briefly described above.

Multiscale neuroscience involves the commitment that the brain is composed of complex networks of interactions and is organised hierarchically in a similar fashion [16, 17]. Within this multiscale framing, the brain can be studied at various levels of interaction, from the micro-, meso-, and macro-scales, and the manners in which they operate together under various context specific circumstances. In a musical context we might study the multiscale neuroscience of auditory perception, showing that pitch registers range from 200-800Hz, rhythm at 0.5-3Hz and neural oscillations between 5 and 40Hz. Here, cochlear resonance and multisensory perceptions can be said to show multiscale activity becoming manifest at different frequency registers. Scaling laws stand as a fruitful framing device in multiscale neuroscience as they speak to invariant features of neurodynamic activity and macroscopic behaviour in musical contexts. For example, participants listening to music have been shown to exploit fractal structures in musical features, specifically in predicting long range tempo fluctuations which are characterised by 1/f scaling from fluctuations at a shorter time scale [18]; such cases will be returned to later. However, it does not follow from there being scaling phenomena in musical contexts that music

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[1] Ontological concerns commonly surround the premise that the function of a holistic unit cannot be reduced to the sum of its functionally dependent parts, whereas explanatory uses maintain that in offering an explanation of a phenomenon it is insufficient to merely offer a functional explanation of the constituent parts.

itself can be characterised as a multiscale object of study. This needs further elaboration and to speak of music (coherently) as multiscale in its own right must be justified.

Scaling phenomena are not novel discoveries of the 20th and 21st centuries. The quantification of music and sound in the Western music tradition can be traced back as early as the Pythagoreans who discovered an inverse scaling relation between the length of a vibrating string and the resulting pitch, making way for their later discovery of the regular frequency ratios between the perfect musical consonants and pitch at a smaller scale [19], p.3; from this grew fields of sound analysis and the study of musical structures. These mathematical considerations of music and sound allow for certain conceptual transformations, such as considering the likes of music and speech as signals. From this point of departure, musical signals can be investigated for multiscale signatures, such as hierarchical organisations or nested regularities in the likes of tempo, beat and metre. While forms of traditional Western music are open to formulating music structures in discretized terms and choosing various separations of melodies or harmonies for statistical analyses (which the Pythagoreans fruitfully exploited), other forms of music resist this. In African and Caribbean musical contexts that make use of responsorial structures, for example, such (statistical) treatments of music are contrary to their philosophy [20] and "playing one part alone is antithetical to the way that musicians hear the music" [21] p.29. So, signal-like treatment of these musical forms does not happen easily. While the goal of this paper is to offer a review of multiscale phenomena in music and its relation to the multiscale nature of brain and behaviour, it is necessary to delineate our purposes as belonging to contexts in which it does make sense to speak of, and treat, music as multiscale from those that it does not. With this systematic analysis of music in the Western tradition as our backdrop, we can coherently proceed in identifying structures in music and in the brain that exhibit multiscale phenomena.This is to say, we draw an important distinction between scale free structure and scale free dynamics, both of which are present in systems that operate near criticality (such as the brain), and show how such structures and dynamics are intimately intertwined.

3. Scale Free Structures

An important distinction that is common practice to make in the literature on scaling laws in the life sciences is between scale free structure and scale free dynamics [13]. Scale free structures in complex systems are characterised by geometric, topological, or connective regularities at different levels that are invariant at temporal or spatial scales. This is to say, there is a statistical reflection of structural features at one level to another, and such structures are central to enabling the preceding scale-free dynamics. Scale free structures that pertain to music cognition include hierarchical temporal structure, long-range temporal correlations, and musical information, and will serve as the limited number of instances addressed throughout this paper. This will pave the way for how scale free dynamics arise in various contexts of music performance and activity; namely, resonance and entrainment, power law distributions, and 1/f scaling.

3.1 Hierarchical Temporal Structure

Common to music, speech and song is hierarchical temporal structure [22, 23]. It has been suggested that similarly organised structures and principles among brains, bodies and environments enable organisms to thrive in their environment [13], and musical activity and performance may be one such manifestation of this similarly organised thriving through mediating multiscale and scaling mechanisms. Investigations into hierarchical structures in music have been carried out in numerous registers, from the fundamental organisational principles across music and song [24] to the specific statistical treatments of nested properties within musical structures [25, 26]. Ours will focus on the temporal domain of these different registers so as to outline the features of extracted signals across multiple timescales that are hierarchically related through multiscale properties and scale invariance.

Hierarchical temporal structure is intuitively apparent in music given that musical activities span rhythmic milliseconds, melodic phrases, and orchestral symphonies. However, various approaches to the statistical treatments of such structures can be taken to comprehensively demonstrate music as a multiscale phenomenon that exhibits significant complexity. One such method is through discretizing notations and musical features (such as rhythm, metre, or timbre) and investigating their interrelations. In these treatments of temporal structures the object of study is specifically the “syntactic organisational principle of musical sequences by which elements are organised in terms of subordination and dominance relationships”. [27], p.15444. These are systematic approaches taken to formalising embedded features in units of musical information that can be sensibly quantified and analysing how such embedded syntactic structures are processed by the brain [27]. With this as the research context, studies have proceeded to show that in order to successfully differentiate between auditory tone sequences in musical pitch that were characterised by fractal structure, musicians have been shown to perform significantly better than non-musicians [28]. Further, this relation between syntactic structure and processing mechanisms in the brain have been developed through imaging techniques such as fMRI and MEG, showing that the specific cortical areas, including Broca’s Area, the inferior frontolateral cortex, ventrolateral premotor cortex, and anterior superior temporal gyrus are central to the processing of musical structures such as varying sequences of regular and irregular chords [29] and more general harmonic, melodic and rhythmic structures [30].

Other treatments of hierarchical temporal structures in music may forgo focusing on discretized units and instead isolate features of events over a period of time and offer insight into the nested nature of other events at smaller timescales [23, 31]. This measuring of hierarchical structures involves the quantification of various brain and music related events in the temporal domain that have nested clusters of events at shorter periods. [23] show that within the amplitude envelopes of different musical phenomena, ranging from jazz and classical genres, to bird and whale song, there are clustered peaks of activity and "the smallest clusters can group together to form larger clusters of clusters over longer periods of time, and so on, to form hierarchical temporal structures" [23], p.2, doing so in a scale-free manner. More precisely, the amplitude envelope in different forms of speech and song are multiscale event features that follow self-similar power law scaling across smaller timescales or the same signal envelope. These examples of scale free structure in music are essential to highlighting music as a multiscale phenomenon in its own right, however, it is only when considered in conjunction with the scale free dynamics that are interrelated with structure that one can investigate whether scaling structures in music serve broader purposes in relating to similar structural organisations in the brain and body.

More is revealed regarding the interaction of scale free structure across brain, body, and environment when we consider other correlational structures that are brought about outside the temporal domain, such as spectral organisations. Although different to hierarchical temporal structure in brain and music, multiscale organisations in the spectral or frequency domains are intimately dependent on the temporal organisations we have been considering. Low frequencies that are not overtly perceived by the listener can be seen to still influence activity in the motor system and are taken as evidence for the fundamental role played by the vestibular system for rhythm perception [32]. Further, different organisations of metric levels have a causal influence on specific body sway movements when listening. Metric levels of period one afford movement in the anterior-posterior direction of the body whereas higher levels at periods of three and four enable movement in the medio-lateral direction [26]. So, outside the correlational structures in the temporal domain, other nested structures have similar multiscale relations that become manifest as mediating relations between brain, body, and music, often in scale free ways (addressed in the section ‘Power law distributions’).

3.2 Long Range Temporal Correlations

Long-range temporal correlations are measures characterised by an autocorrelation function that slowly decays according to a power law in the temporal domain [33]. This ubiquitous structure across a wide range of neural and behavioural measures has emphasised various important properties of adaptivity in complex systems, such as self-organised criticality in the brain, or the ability for organisms to continually attune to invariant features of their environment by way of resonance or synchronisation [34, 35]. More precisely, long-range temporal correlations have been shown to be scale-free at the level of neural oscillations where bursts of activity do not preside at a dominant timescale [36], blood oxygenated level-dependent fMRI measures of macroscopic brain activity [37], in fluctuations of heartbeat [38], and in postural sway [39, 40]. Given the widespread occurrence of this signature of scale-free structure it is reasonable to look for the presence of long-range temporal correlations of musical activity and whether this statistical property is a feature of music itself. Might such a parallel be a result of the reflection of scale-free correlation structures between the musician and music?

At the microscopic scale, evidence for long-range temporal correlations has been shown in cortical activity, specifically in MEG recordings of phase-tracking between neural signals and tone sequences [41]. This study demonstrated both phase correlations and phase coherence serve to measure long-range temporal synchronisation and patterned pitch sequences, specifically between the amplitude of neural oscillations and the modulation amplitude of the stimuli. Similar studies have shown that such correlations between neural activity and long-range temporal structure in 1/f signals enables higher rates of information transfer between both systems, and how such exchange varies across V1 neurons is affected by different mean temporal frequencies in a signal [42].

While long-range temporal correlations have been outlined in the brain's relation to musical features, there is an important relationship between this scale-free structure in the brain and scaling dynamics at the level of the behaviour, where individual variability in scale-free behaviour of the body is explained linearly by corresponding variability in neuronal scaling laws [43]. While the brain exploits scale-free structure in both its own organisation and in information exchange with musical features, neglecting similar scale-free features in the body would be to neglect the multiscale brain-body relations with the environment. At the level of the motor and nervous system, physiological research shows that the auditory periphery may be acoustically structured in such a way to attune to the spectro-temporal statistics of our acoustic environment [44], (see also [45]). Likewise in motor control and human gait dynamics the statistical structure of gait mirrors the structure of musical auditory cues while walking, demonstrating the long-term coupling between auditory and motor phenomenon [46]. These studies can be put forward to support the case that structural features of the person attune to structural features of the environment in the contexts of music, a hallmark of adaptive behaviour more generally. So, multiscale relations between two complex systems at different temporal scales, the person and music, and neglection of the body (so far considered as the motor and nervous system) in studying scale-free structure in musical activities would be to neglect significant dynamic interactions between two multiscale complex networks.

3.3 Musical Information

The consideration of musical information as a scale-free structure must be clarified and developed in this context given that information as a conceptual tool has been applied historically in a wide variety of ways. 'Information' differs from the scale-free structures we have so far evaluated as it can be considered as a measurement of system complexity rather than being a genuine scale-free structure in its own right. [9] give a succinct framing for the motivations of these uses of information in a complex systems register, where recent research is interested in "exploit[ing] behavioural measures for exploring the intimacy of a system, and more precisely, to obtain a better understanding of the principles that underlie this 'optimal complexity' between order and disorder" (p.462). Information stands here as a means of investigating the organisational and functional interactions between systems and their correlational properties where the dynamics of exchange is central [47]. So, rather than being a property or feature of the system that displays statistical self-similarity across scales, musical information is in this way a manner of framing and measuring musical features, such as pitch, rhythm, timbre, and can be used to demonstrate the scale-free nature of these quantified features along with other methods of complex time series analysis.

Musical information can here be understood as the application of statistical methods to musical features during performance and activities, and making use of information as a formal tool in musical contexts. Importantly, the formal development of information places bounds on how we speak of the interrelation between music and brain, and shapes how scale-free mechanisms between the two become manifest through coupling, resonance, entrainment etc. [48]. Musical information specifies the interactions or exchanges between systems, whether between music and the brain or between musical bodies, that allows for structural formations of “spatiotemporal patterns of activity on multiple temporal and spatial scales within the nervous system" [48] p.201.

More generally, musical information specifies a rigorous formalism, usually with an information theoretic underpinning, for the regular dynamical mechanisms that take place when interacting at similar scales, such as signal resonance between the nervous system and musical patterns when considered at the appropriate scale [49], the purpose of which is to understand the principles that underlie these functional interactions. One can coherently specify note duration, rhythmic onsets and pitch signal as musical information, and how participants anticipate such information in well-specified musical tasks, such as through finger-tapping [18], or listening to musical tones [50]. Musical information in these cases is taken as a representation for temporal or spectral structures. It can be framed that information transfer is determined by the influence that the crucial events of one system exert on the time of occurrence of the crucial events of the other [11], with volume of musical signals taken as a proxy for measuring the transfer of musical information between two systems in this case. Musical information as a structural measure for task specific musical activities is central to scaling relations in multiscale systems as it speaks to the close association between structure and dynamics. It is in virtue of this treatment of complex systems in music cognition that one can quantify the likes of hierarchical temporal structure and long-range temporal correlations, and the ways in which scaling mechanisms operate within these structures.

4. Scale Free Dynamics (across brain, body, multiple bodies)

We have made use of the distinction between scale-free structure and scale-free dynamics to bring certain invariant connective and organisational correlations to light and not conflate them with the scale-free dynamic activity itself. Scale-free dynamics can be understood as the invariant regularities of system activity that is often enabled by the scale-free structures in which they are embedded. We shall proceed in outlining some of these regular dynamic patterns as they operate across scales and in what ways they are closely tied to the scale-free structures above.

4.1 Resonance and Entrainment

Resonance and entrainment are intimately related. It is understood that entrainment occurs within a resonance frequency range and recent theories have hypothesised that the co-occurrence of these mechanisms are directly responsible for the likes of beat and meter perception [48, 19]. Resonance has been defined as “the increase in amplitude of oscillation in a physical system exposed to a periodic external force of which the driving frequency (or one of its component frequencies) is equal or very close to a natural frequency of the system” [51] p.44. Resonance between two complex systems makes way for identifying isomorphic patterns of activity between the two and offers a formal means of modelling such activity through recurring patterns of information transfer [52]. Music has proved useful in developing our understanding of resonance as both a useful theoretical concept and a fruitful modelling tool. Musical resonance takes place at multiple scales, ranging from neural resonance to a musical stimulus, cochlear resonance to different registers of pitch and metre frequencies [19] and sensorimotor synchronisation to musical features [53]. It is through these multiscale forms of resonance, and the models that describe these structures, that we can speak of the specific mechanisms involved in the information transfer and isomorphic patterns of activity between systems in a musical context and bring properties of resonance to light. For example, central to pitch perception is the intimate coupling of the cochlea to hair cells that act as frequency oscillators. The frequency determined by this coupling relation resonates with external frequencies of the environment at different registers and determines the perception of sound [54]. The resonating structures that have been shown to underlie pulse perception, spanning both auditory and motor systems, provide formal representations of how finger tapping significantly reflects different musical tempi distributions [51, 55]. It has been proposed that by way of such forms of involuntary resonance at the cochlear and neural scale that the motor system is primed for entrainment to rhythms at a larger scale [56], making way for accounts of entrainment that show multiscale dynamics of greater sophistication across brain and body in musical contexts.

Entrainment follows from this process of involuntary resonance where various stimuli are present and interacting with a system within a particular frequency range, giving rise to oscillations by way of interactions at some scale. However, entrainment differs insofar as such stimulus coupling influences the oscillation’s phase where the synchronisation that follows can be understood as an adaptive function [57]. To be more precise, entrainment involves the synchronisation of systems to the same rhythm or frequency and from this one can influence, and predict, change in the dynamics under perturbation; it is these dynamical changes under fluctuations in oscillation that is considered an adaptive process that entrainment characterises.

Both resonance and entrainment in brain and body speak to the synchronisation of sensory modalities to aspects of the environment at varying scales, yet differ in the sophistication of phase alignment and dynamics of entrainment. [58] usefully distinguish between three types of entrainment as it occurs across different scales; neural entrainment, overt motor entrainment, and covert motor entrainment (p.2). Neural entrainment comes about through the synchronisation or phase locking of neural oscillations in time with an external stimulus. In music activities, beat, rhythm or pulse are regularly taken to be such external stimuli. [59] demonstrate neural entrainment, specifically in beta (15–30 Hz) and gamma (>30 Hz) oscillations of the auditory cortex during passive music listening. More specifically, it was shown that these cortical rhythms entrain to stimulus pulse where such synchronisation was not the case before the stimuli were induced. Similar results have been corroborated in [50]. Taking beat as an external stimulus, neuronal entrainment through EEG measurements occurs through periodic neural responses becoming entrained to beat and metre frequencies [60, 61]. Overt motor entrainment specifies a coupling relation between body movements (specifically activity in the CNS and motor system) and sensory stimuli. The importance of overt activities such as finger-tapping [62, 63], postural sway fluctuations [56] or ancillary gestures [64] in the context of music lie in the various manifestations of synchronisation at different spatial or temporal scales in the body that overt motor entrainment characterises. Lastly, covert motor entrainment is a type of neural entrainment though it refers specifically to coupling between sensory stimuli and neural oscillations supporting body movement, but is absent of overt action. Covert motor activity has shown that brain and body entrainment are central to beat perception [65], however, there are significantly fewer resources on covert motor entrainment in music cognition and stands as an area for future directions of research.

While these studies bring to light resonance and entrainment in musical contexts, there has been little research into the resonance or entrainment across brain and body to stimuli that exhibit specific scale-free structure or scale-free dynamics. So, while resonance and entrainment in music offer a wide variety of support for the multiscale properties across the brain and body, further research is necessary to say more regarding the scale invariance of such phenomena.

4.2 Power Law Distributions

Power law distributions are one signature of scale-free dynamics whereby, in a minimal sense, a variable is a function of another variable raised to some power and it is this constant scaling exponent of power laws that specifies how scales relate across a system. A power law distribution involves the resistance of the characteristic autocorrelation function to decay, implying a long-range correlational structure over time in the temporal or spectral domain. It is here we come to see the intertwining of scale free structure and scale free dynamics. Such distributions have been shown to be ubiquitous at different scales of neural activity and across functional networks at the mesoscopic level [66]. [67] demonstrate power law distributions coming about through nested frequency organisations in the micro-scale activity of the brain obtained through EEG measures. Furthermore, this study made use of other noninvasive imaging tools to show power law variation of power spectra at the macro-scale of the brain, where fMRI signals of 21 recorded brain regions reliably followed power law distributions (see also [4]). So, as above, the likes of hierarchical temporal structure of the brain can be specified across micro-, meso-, and macroscopic activity [17], and the temporal organisation across these multiple scales enables nested frequency activity described through power law distributions. [67] particularly emphasise such structural organisations in allowing for statistical properties of the brain, specifically power law distributions, to reflect or adapt to self-similar statistical properties of the environment. These observations might be extended to music cognition in showing that scale free structure in the brain and body might arise in interaction with the scale free structures in music and enables various scale-free dynamic activity, which we shall later see is being hypothesised as 1/f resonance [68].

Recently, an area of research has emerged that exploits the multiscale properties of music, and specifically scale invariant properties, in using scaling laws as a means for music characterisation and classification [69]. [23] show that Allan factor quantities of hierarchical temporal organisation in music follow a power law distribution. So, only in cases where there are power law distributions there are nested temporal organisations, in this way speaking to the multiscale nature of various forms of music and song using scaling laws. Similarly, Levitin and colleagues make use of power law scaling in the spectral structure of musical rhythms across different Classical pieces of music for famous composers [25], demonstrating the difference in particular composers using power law scaling as a means of comparison. This work improves on other work that also identified 1/f power laws in Western Classical music [70]. It is through such classifications of musical features and genres according to power law scaling that scale invariance has been fruitful to music analysis and brings to light how musical features at different scales contribute to musical characteristics in different genres.

4.3 1/f Scaling

1/f noise and scaling make us rethink the traditional framings of noise as a source of system uncertainty or randomness. Signal randomness and determinism can be characterised by the correlations of increments in a time series, where Brownian noise has no correlations and is thereby considered a random walk, and white noise signals are strongly correlated so highly deterministic. 1/f noise (pink noise) is defined by fractional determinism due to it being mathematically described by fractionally differenced white noise, and is thereby an intermediary between the two, white and Brown, with differing degrees of correlational structure. Noise as a scientific concept can be specified as local variance, which has traditionally been the case in cognitive science, or as serial correlations of varying degrees over time [9,71]. It is cases of serial correlations that regularly concern the role of 1/f noise in neuroscientific and sensorimotor accounts of adaptive behaviour and has placed 1/f scaling mechanisms in brain and behaviour at the forefront of scientific enquiry today. 1/f (pink) noise demonstrates optimal system complexity in its navigating between Brownian randomness and white noise determinism, and is considered a hallmark of scale-free dynamics.

1/f scaling is a scaling mechanism found in multiscale systems that is specified by a power law in the temporality or the spectral intensity of a signal. To be more specific, 1/f scaling refers to a form of serial correlation between the frequency and either the temporality or intensity of the power spectrum of a signal, the index of the temporality or intensity demonstrating the different mean temporal frequencies to which a feature of the signal is autocorrelated. It is common practice for {\alpha} to specify the autocorrelation of temporality, and is present at an index <0.5 and >1, and for {\beta} to refer to the autocorrelation of spectral intensity across a signal, present between indexes of <-1 and >3. Like power law scaling, 1/f scaling is intimately related to the scale-invariant structures outlined above as its autocorrelation function shows resistance to decay, signifying that these time series follow long-range temporal correlations [69].

1/f scaling has been demonstrated at the micro-scale of the brain in neuronal activity where it is suggested that this ‘optimal complexity’ exhibited by 1/f signals allows for efficient neuronal coding and adaptation to natural stimuli [42]. It has reliably been shown to be a multiscale dynamic insofar as it spans the micro-, meso- and macro-scales of the brain [13], fluctuations across the body [72, 73], and across multiple bodies [74]. Given its universality across systems and social phenomena, it is reasonable to turn specific attention from natural stimuli that exhibit 1/f activity to specific musical stimuli and how such scaling is made manifest in these musical contexts.

Voss and Clarke’s seminal (1975) paper shows fluctuations in musical pitch and loudness follow 1/f distributions, concluding that white or Brownian noise distributions are less pleasing than 1/f^{\beta} noise in music [75], (see also [76]). This hypothesis has been further investigated by way of pitch fluctuations in musical spectra that are taken to further demonstrate 1/f scaling as arising in performance and composition from the negotiation between surprise and predictability in listening to music, placing a large part of the “pleasurability” of music on its statistical self-similarity [25, 77]. Other research has followed this relation between 1/f activity and predictability by showing the ways in which 1/f stimuli can be used to enhance the ability to predict rhythmic cycles and tempo fluctuations; musical information that is characterised by 1/f fluctuations is used to efficiently anticipate tempo and rhythm in music specific tasks [18]. Such findings potentially offer new modelling techniques for medical and therapeutic approaches to Parkinson’s disease [46, 18]. So much like 1/f scaling across brain and features of the environment has lead to hypotheses of scale invariance as an adaptive function that the organism makes use of/exploits, it has been suggested in musical contexts that brain and music too follow similar dynamic laws in order to afford greater interaction between the two [78], and potentially offers novel clinical treatments for motor inhibitions through audio-motor assessments.

The theme of universality in scaling mechanisms recurs in music cognition through 1/f-like phenomena and associates well with our treatments of resonance and entrainment. 1/f activity can be considered as one form of demonstrating how systems engage in maximal information exchange and displays isomorphic patterns across interacting scales of complex systems [52]. The implications of a 1/f resonance framing have been carried out in a musical register where it has been found that musical stimuli characterised by 1/f activity influence brain activity and heartbeat rhythms while listening to music in a manner that coheres with the accounts of resonance outlined above [68]. Such a framing of 1/f mechanisms as a resonance phenomenon offers a differing account of the significance of fractal dynamics in music, pushing back against the hypotheses that find the "pleasurability" of music in 1/f properties, and instead positing the "pleasurability" to be grounded in the interaction afforded between the acoustic scaling with the scaling behaviour of neuronal dynamics; an interaction of resonance between brain, body and music that results in pleasurable experiences of music [68], p.9. Moreover, the significance of these findings lie in the considerations of resonance, not as a stochastic phenomenon, but rather as a scale-free dynamic that enables optimal information transfer between multiple systems, again the brain-body-music system at multiple scales.

5. Methods of quantifying multi-scalability

The considerations towards multi-scalability and scaling mechanisms in biological and cognitive systems entails the harmonising of theoretical models with empirical phenomena, with profound implications for areas of coordination dynamics, biocomplexity, and statistical mechanics [79]. While it has mostly been the theoretical considerations that have concerned us so far, it remains necessary to outline how such phenomena are measured and quantified for the bringing about of theoretical models. Signatures of multiscale systems, such as scaling laws, may not be immediately evident in neural or behavioural measures so often reconstructions or transformations of these time series are necessary. The motivations for quantifying multi-scalability lie in the potential detections of invariant features or properties nested in complex time series, and in particular, the quantifying of scaling relations in a time series involves the identification of correlational structures across scales. The following methods are a limited case of identifying such correlational and recurring structures in multiscale phenomena and are namely complex time series analysis, recurrence quantification analysis, multiscale coefficient of variation analysis, and Allan factor analysis. These methods will be directly tied to the scale-free structures and dynamics previously outlined and will demonstrate how such scale-free invariants are brought to light.

It is important to note that these methods of investigating multiscale properties in time series do not necessarily provide a strict quantity for some scaling variable or exponent and some go so far as to distinguish their multiscale measures from being conflated with scale invariant measures. So, while we have paid particular attention to scale invariance in multiscale systems, there may be a seeming conflict between the ability to comprehensively quantify multiscale features and the resistance to this being a quantity for scale invariance. We do not contest this but also recognise that these methods of complex analysis often make use of measures that evaluate self-similarity or correlational properties of time series, particularly ones characterised by pink noise-like activity. This is to say, there are useful measures in these methods that include the Hurst exponent, correlation dimension, or wavelet variances that can fruitfully bring quantities of scale-free structure/dynamics to light while at the same time not explicitly demonstrating scale invariance in a manner done by the likes of multifractal detrended fluctuation analysis (MFDFA).

Lastly, theoretical concepts such as multi-scalability, interactivity and scale invariance are used in multiple ways that may not easily cohere. It has been shown elsewhere that it may be the case that scale-free activity takes place in the brain or body but this does not guarantee multi-scalability at the same time [80], and as we have mentioned, certain tools of analysis may serve one purpose but not the other. For example, in treatments of power law scaling in local interactions of a system, such as cases used to support self-organised criticality (SOC) hypotheses, this is not enough to show (at the same time) that the system shows multi-scale phenomena as the interactions pertain to one local scale. We wish to highlight that the use of multiscale methodologies often reliably reveals invariant structure or dynamics nested in a system across scales that are not otherwise apparent, but in other contexts more is needed to justify a system as multi-scale alongside the fractal treatment of a phenomenon.

5.1. Complex systems time series analysis

Complex time series analysis in the cognitive sciences is the application of statistical methods to time series measurements recorded by way of various investigative tools at the level of brain, body, or social group, and the conducting of analysis of how such time series behave over time. The analysis of these behavioural measures intends to make way for novel hypotheses to be made, the identification of shortcomings in current analytical methods, and the wider dissemination of these statistical tools across other fields of science. Complex systems time series analysis is central to the purpose of this paper as it speaks to the theoretical themes of universality, adaptivity and interactivity found in multiscale neuroscience and music.

Central to both complex time series analysis and scaling laws is the methodological concept of autocorrelation, the process of correlating variables in a time series at different lag periods. It is this process of correlation between some prespecified variables or parameters that bring to light certain self-similar features at different scales in system dynamics. Examples of these include the Hurst exponent or self-similar parameters and are used by methods of analysis such as Detrended Fluctuation Analysis to show scale invariant properties. Complex systems time series analysis tends to approach time series measures differently to traditional methods of analysis through means of averaging and standard deviations, and instead investigates the trends of variations over time [72]; rather than variations arising through system perturbation outside of experimental conditions or through unwanted noise, it is studied whether variations over time display self-similarity, recurrent, or nested features across scales, and what such characteristics tell us about the system. It is this that the following methods take as their starting point in outlining multiscale and scale free phenomena in musical activities and performance.

5.2. Recurrence quantification

Recurrence quantification analysis (RQA) is a nonlinear method of analysing the complex relationship among variables that are recurring dynamical features nested within a time series at some scale; RQA allows for such features to be objectively compared and processed as an ensemble of complex relations [81, 14]. In other words, RQA is a formal means of quantifying and visualising recurrent patterns embedded in a reconstructed time series according to prespecified parameters. Identification of these recurrent patterns have been widely used in the cognitive sciences to speak to self-reports of human experience [82], multiscale relations within time series' of motor control and postural sway [83], and synchronisation and coupling relations in social interactions [84, 85]. RQA addresses the multiscale structures and dynamics emphasised above insofar as it is a fruitful method in highlighting the nested patterns in hierarchically organised systems that may not be immediately visually apparent, and can also be framed as a means of investigating the mutual information shared between two time series by way of cross-RQA.

RQA has been evoked in contexts of music cognition and performance in order to demonstrate the invariant structures found in music and brain activity or bodily movement during performance. Demos and colleagues investigated the measure of recurrence in postural sway across entire musical performances of individual musicians, varying the styles of music they played. Specifically looking at rate of recurrence and stability of recurrence, postural sway in the medio-lateral direction was influenced by the style of music being performed as musicians' postural sway systematically changed during different musical phrases and is taken to support the view that bodily movements reflect musical features of the pieces being played [86, 87]. Scaling upwards from individual case performances, RQA has been further used to outline the emergence of coordinated activity during ensemble performance, specifically speaking to the dynamics underlying an uncoordinated-coordinated transition as a conductor orchestrates the played musical score [88].

5.3 Multiscale coefficient of variation analysis

Multiscale coefficient of variation analysis (MCVA) is a novel analytical tool that serves the purpose of measuring temporal variability across both short and long timescales. Common methods of measuring temporal variability across a time series are optimally suited to long timescales in order to specify long-range regularities, and identifying self-similar structures at this scale, yet are unreliable for doing so at short periods [89]. Multiscale coefficient of variation supplements this shortcoming in its ability to identify different ranges of correlations in time series data through measuring how a coefficient of variation changes at short and long intervals (short being defined as <1,024 data points). It does not follow from this that it functions as a means for quantifying scaling relations - there is an inherent dependency on long-range correlations or ‘memory’ in such scaling relations that MCVA does not necessarily account for, especially at short timescales[2]. This would also risk confusing multi-scalability with self-similarity.

In practice, [89] took material from previous studies to see how MSCV might reveal novel insights into durational variability across the musical themes of English and French composers. Here, it was demonstrated that in comparison to commonly used coefficient of variation (CV), MSCV shows the multiscale features of musical pieces, in this case the rhythmic durations, that were not otherwise outlined through CV. In an experimental setting, MSCV has been fruitfully applied to demonstrate the coupling relations between postural sway and musical structures, where the multiscale features of postural sway entrain to the multiscale features of musical groove [56]. The global entrainment of postural sway to music is stronger for low-groove music than for high-groove music as sway entrains to changes in variability over time and to music’s metrical structures.

5.4 Allan factor analysis

Allan factor (AF) analysis is a means of calculating the power law in clustered events that are nested within a longer series and has been used to uncover fractal structure in neuronal spike trains [90, 91], hierarchical temporal structures in speech [92, 93], and the same in musical genres and song [23]. AF analysis involves calculating the Haar wavelet variance for a certain range in a timeseries, which are tilted (the distributions are adjusted) into windows. The events within each window are counted and the differences in counts between adjacent windows are squared and averaged, which are divided by twice the mean count that yields an estimate of AF variance A(T) [23] p.4. A(T) will act according to a power scaling law in the presence of clustered events, and this serves the purpose of revealing both hierarchical organisations and autocorrelated structures, thereby speaking to both multiscale properties and scaling dynamics in a system. This is the method used by [23] to quantify both multiscale structure (hierarchical temporal organisation) and scale-free dynamics (power law distributions) to differing degrees across a wide range of speech and song in nature. It can be argued that this exceeds the performance of the likes of Multi-Fractal Detrended Fluctuation Analysis as both offer a coefficient of variation that provides insight into scaling activity, but AF analysis further informs of the patterns of hierarchical clustering that is not severely influenced by musical features such as pitch and tempo.

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[2] This is not to say that there are not scaling dynamics to be found at short timescales, it can be the case that such correlations at a short scale are nested within long-range correlational dynamics. Only MCVA does not serve as a tool to bring these to light.

6. Conclusion and Future Directions

This paper has explored the emerging themes of scale free mechanisms in music and neuroscience aided by distinguishing structure from dynamics. What might the likes of embodied cognition draw from the methods and theoretical considerations of multiscale neuroscience through a scaling law framing we have sketched above?

First, it would be prudent to recommend against reifying any form of scale-free structure or dynamic in environmental or behavioural measures. The universality of these scaling mechanisms in the brain, body and environment might prompt a conclusion that they stand as having a privileged fundamental structure that adaptive behaviour orients around or is attuned to. Multiscale neuroscience suggests otherwise that our inquiries can be specified at different scales and in doing so, demonstrate multiple forms of structure and dynamics that contrasting research paradigms can attribute importance to some findings over others. We saw one such example of this in the role 1/f scaling plays in pleasurable experiences of music, on one account "pleasurability" being in the 1/f properties of music itself, while others emphasise the resonant dynamics between music and listener that 1/f scaling affords.

Secondly, in our outlining the literature in these research domains we found areas worth further investigation. Neural entrainment and overt motor entrainment in music listening and performance have enjoyed recent published findings that reveal multiscale properties of musical activities across the brain and body, but there is noticeably little research into covert motor entrainment and music cognition. We believe that this additional research into covert motor entrainment is important to developing accounts of entrainment that musical activities have so far been very fruitful in bringing to light.

1/f resonance offers a promising route into highlighting the isomorphic patterns between two or more systems, particularly in musical contexts. There has been some research progress in this direction to do with 1/f resonance and music relations but, as demonstrated above, entrainment offers more informative accounts of adaptive behaviour within resonance frequency ranges. We suggest the need for more specific investigations that pertain to 1/f mechanisms and entrainment in music cognition that 1/f resonance has so far fallen short of. This would prompt investigations in the direction of; how does entrainment operate within the 1/f resonance frequencies already investigated? How do the dynamics of 1/f entrainment converge or diverge from the wide body of research on entrainment as we know it so far? Does our predictive capacities of entrainment change when looking at 1/f-like entrainment between systems?

We believe that it would be beneficial for the field of music cognition to draw from these issues in multiscale neuroscience in thinking about the problems of the embodied brain across different scales of interaction in a musical environment. Further, close attention into how such musical environments brought about at the level of the individual brain and body (in contrast to that at the scale of group performance) offers potential insight into transitions or coupling relations that have not yet been made explicit. We might look to recent exciting work that has shown a progression in this direction; the likes of [88, 94, 95] investigate musical contexts spanning individual performances and collective ensembles, alongside their neuroscientific underpinnings, in how musical environments are brought about and shared. We hold that a scaling law framing, similar to ones sketched above offers a promising path forward in addressing some of these future questions in the multiscale interactions of music cognition.

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