

# Music cognition: Bridging computation and insights from cognitive neuroscience

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## Goals and Scope

In recent years, computational models have become an increasingly important part both of cognitive science and cognitive neuroscience. In tandem with these developments neuroscientific and cognitive investigations of musical experience and behaviour have been gathering pace. In this context, music cognition constitutes a rich and challenging area of cognitive science in which the processing of complex, multi-dimensional temporal sequences can be studied without interference of meaning or semantics (see Pearce & Rohrmeier, 2012, for a review). Because of its complexity and well-defined problem-space, computational modelling of music witnessed a rapid growth of successful higher-order modelling approaches. This workshop investigates computational modelling as a bridge between cognition and the brain, with a focus on understanding the psychological mechanisms involved in perceiving and producing music.

Many approaches have been taken to modelling the large variety of different cognitive processes involved in music perception and creation involving various modules of basic structural processing, statistical learning, memory, as well as motor, emotional and social cognitive processes. Recent computational models range from hierarchical, rule-based systems for representing harmonic movement inspired by probabilistic grammars for language, through oscillator based network models for modelling metrical and tonal perception, to probabilistic methods derived from machine learning for modelling dynamic learning and predictive processing of style-specific musical structure. Turning to cognitive neuroscience, recent years have seen increasing interest in advanced computational modelling of EEG and fMRI data used to distinguish brain regions responsible for the processing of different aspects of music (e.g., rhythm, pitch, timbre, harmony) and the functional connectivity between them. The purpose of this symposium is to bring together and display current research trends towards a synthesis of these two research areas linking the parameters and subcomponents of cognitive models of musical processing to functional and anatomical properties of the brain.

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## Petri Toiviainen and Elvira Brattico Decoding the musical brain during naturalistic listening

Encoding, or prediction of neural activation from stimulus, is a common modeling approach in neuroscience. In our recent neuroimaging study, we applied encoding to predict brain activity during listening to different pieces of music from an extensive set of musical features computationally extracted from the pieces, and found widespread brain activation, including auditory, limbic, and motor areas (Alluri et al., Neuroimage, under review). With such complex and distributed neural activation, evaluation of different encoding models is not straightforward, because the goodness of prediction is difficult to assess. Decoding, or prediction of physical or perceived stimulus features from the observed neural activation, has the potential benefit of a more straightforward model evaluation because of easier performance characterization in terms of, for instance, correct classification rate.

In a series of experiments, our participants were measured with functional magnetic resonance imaging (fMRI) while they were listening to three different musical pieces. Subsequently, musical features were computationally extracted from the pieces, and continuous emotion ratings were collected from the participants. For decoding, the fMRI data were subjected to dimensionality reduction via voxel selection and spatial subspace projection, and the obtained projections were subsequently regressed against the musical features or the emotion ratings. To avoid overfitting, cross-validation was utilized. Different voxel selection criteria and subspace projection dimensionalities were used to find optimal prediction accuracy. The decoding results and the challenges of the approach will be discussed at the symposium.

## Psyche Loui Behavioral and DTI Studies on Normal and Impaired Learning of Musical Structure

One of the central questions of cognitive science concerns how humans acquire knowledge from exposure to stimuli in the environment. In the context of music, knowledge

includes the structure of harmony and melody that govern how musical pitches are combined. While people of all cultures and ages show some knowledge of the structure of their music, people with tone-deafness (also known as congenital amusia) show a lack of behavioral sensitivity to harmony and melody. Here we combine behavioral evidence from subjective ratings, neuroimaging evidence from Diffusion Tensor Imaging, and neuropsychological evidence from tone-deaf individuals, to support the thesis that much of what we know and love about music is acquired via statistical sensitivity to the frequency and probability of occurrence of events in the auditory environment. This statistical learning mechanism relies on intact white matter connectivity between temporal and frontal lobe regions, and may subserve multiple auditory-motor functions including language as well as music.

### **Edward Large and Ji Chul Kim** **A Universal 'Grammar' for Music**

Since antiquity, science has asked whether mathematical relationships among acoustic frequencies govern the perception of musical relationships. Modern psychophysicists rejected this approach, citing evidence that the auditory system performs a linear analysis of sound. Cognitive psychologists have since relied primarily on statistical learning to explain music cognition, despite continued demonstrations of the importance of frequency relationships. Today evidence is rapidly mounting that the auditory system is highly nonlinear, inviting reevaluation of the role of frequency in constraining the perception of music. Here, we present a dynamical systems analysis of auditory nonlinearities that predicts substantive universals in music perception and cognition. This approach explains perceptual ratings of Hindustani raga not only by encultured listeners, but also by listeners who were completely unfamiliar with the music of North India. This evidence suggests that universal properties of neural oscillation explain cross-cultural invariants in the perception of tonal music, implying neurodynamic constraints on the acquisition of musical languages.

### **Martin Rohrmeier** **Computational Models of Musical Syntax**

In order to create the variety of our rich musical experience, Western music employs a complex combination of interwoven features of pitch, rhythm, metrical structure, harmony and melody. Various computational models of music processing are based on local (event-to-event) processing of musical features (cf. Rohrmeier & Koelsch, 2012). On the other hand, a number of theoretical approaches suggest that music involves recursive, hierarchical structures organized in ways similar to linguistic syntax. Further recent neurocognitive research provides evidence indicating that musicians as well as nonmusicians are sensitive to subtle long-distance violations resulting from the underlying syntactic structure. These insights suggest that musical processing is more complex than previously assumed and involves rich mechanisms of

structural parsing and implicit learning to deal with these syntactic features. This talk presents the picture emerging from converging evidence of theoretical approaches, recent experimental work and computational modeling. Probabilistic models of musical syntactic processing based on Hidden Markov Models and probabilistic context-free grammars underpin that the inference of complex nonlocal dependencies from mere exposure is plausible. They further predict experimental data of musical tension and expectancy showing that a variety of features of musical experience can be modeled by such approaches.

### **Marcus Pearce** **Expectation and Emotion in Music Perception: Computational Modeling of Dynamic Cognitive and Neural Processes**

The idea that aesthetic experience of music is dependent on the confirmation and violation of expectation dates back at least to Hanslick. Meyer (1957) further proposed that such expectations depend on probabilistic models of musical structure, acquired through exposure. However, until recently such theories remained largely untested. Here we present evidence corroborating these proposals and filling in some of the details in terms of cognitive and neural processing. First, we show that musical expectations elicited in a range of musical styles result reflect probabilities acquired through a process of statistical learning. Subjective expectedness and uncertainty can be modeled dynamically through time using the information-theoretic concepts of *information content* and *Shannon entropy* respectively. Second, we identify time-locked electrophysiological brain responses to events differing in information content. Third, we show that variations in information content lead to distinct psychological and physiological emotional responses elicited in a live concert of music for solo flute. The results also indicate that expectations and emotion are influenced by factors other than the musical structure such as visual aspects of the performance. In summary this research suggests that musical expectations rely on dynamic probabilistic cognitive processing of musical structure, supported by corresponding neural processes, and generates characteristic physiological and psychological emotional responses.

### **Moderators:** **Marcus Pearce and Martin Rohrmeier**

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