

When the Brain Waits for the Beat: Emotional Priming and EEG Signatures in Rhythmic Expectation

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Abstract

The human brain is a prediction machine, and nowhere is this more apparent than in how it processes musical rhythm. When a beat arrives on time, the brain registers confirmation; when it does not, something more interesting happens. This paper examines the neural mechanisms underlying rhythmic expectation and its interaction with emotional priming, drawing on electroencephalography research and publicly available datasets including the DEAP dataset and OpenNeuro repositories. Grounding the analysis in Huron's ITPRA theory, Meyer's expectation framework, and predictive coding accounts of auditory perception, the paper traces the EEG signatures associated with rhythmic violation, expectation fulfillment, and emotionally primed listening states. Key neural markers examined include the mismatch negativity, N400, and oscillatory activity in beta and theta frequency bands. The findings suggest that rhythmic expectation is not a purely cognitive phenomenon but is deeply entangled with emotional processing in ways that have significant implications for music cognition research, therapeutic applications of music, and our broader understanding of how the brain constructs temporal experience.

Keywords

Rhythmic expectation; emotional priming; EEG signatures; mismatch negativity; predictive coding; music cognition; neural oscillations.

1. Introduction

Since then, many studies on neuroscientific theories have emerged to explain how we understand music through expectations in relation to the process of anticipation and subsequent satisfaction[1]. Over the past several decades, many empirical studies have shown that the brain actively makes predictions of upcoming auditory input rather than merely receiving it; The response characteristics vary depending on whether there is a deviation from these expectations as well as how large this deviation is. Electroencephalography is more suitable for measuring this phenomenon; its high time-resolution capability can monitor in real-time the quick sequence changes of prediction, violation judgment, and reorienting at music rhythms continually demand.

What has received relatively less systematic attention is the link among rhythm anticipation, emotional response. Emotion and expectations do not exist separately while people listen to music, but rather as closely intertwined components that affect the individual's emotional response to sound and how these reactions manifest in brain activity. A listener's emotional state during the listening process forms an expectation mechanism for music perception; When this sense of Expectation is violated, it will trigger corresponding emotions as a response, thereby reinforcing subsequent Expectations. The two-way connection between expectations and emotions in music rhythm perception is the central issue under examination here.

This Paper has three related objectives. To build an initial foundation for exploring the theory of rhythm anticipation and emotional predisposition in neuroscience. Examining the EEG

evidence of the brain's neural signature for rhythmic expectations, violations and emotional priming. Also consider what this evidence tells us about how the organisation of musical cognition is structured and has practical applications in Music Therapy Research on Emotional Regulation.

2. Theoretical Foundations

Theoretical backgrounds related to the concept of rhythmic anticipation and emotional priming in music mainly come from cognitive psychology, neuroscience and some aspects of music theory; As these disciplines develop separately over a long time span without significant cross-pollination or interaction until now.

Meyer's study of the concept of music creation in terms of changing people's Expectations belongs to music theory and Aesthetics; therefore, it does not fall under empirical research. Meyer believes that the emotional Power of Music comes from the sense of anticipation and realization that listeners experience; these two factors are largely acquired cultural knowledge or rather part of our general way of perceiving patterns and continuations. This form has withstood the test of time; it was neither untroubled nor did it prove beyond question that expectations are a component of musical experience but only that such claims accorded with evidence obtained using methodologies that were unknown to him.

Krumhansl's initial psychoacoustics work has shown that listeners create and apply their tonal and rhythmic expectations through certain processes; moreover, there are clear behaviourist explanations as well as physical demonstrations indicating such perceptions do indeed exist in music listening. Her study on tonal structures showed that listeners form an implicit model by perceiving the statistics in music style over time and thus have a subconscious understanding of what will follow. This hidden knowledge is actually the violation of rhythm that leads to such neural consequences as being highly identifiable by non-musicians with formal music education.

Huron's ITPRA theory is a programmatic work rooted in many years of empirical and theoretical research that provides an in-depth study on how Expectations trigger emotions by means of Music [3]. ITPRA defines the five successive responses of imagination, tension, prediction, reaction and appraisal during an attack respectively. Theories are highly relevant in explaining the electrophysiological responses, as they can describe the temporal changes of expectations and reactions accurately enough to provide testable hypotheses about which brain activities occur at what point after a given musical event. The reaction stage, corresponding to automatic response generation after prediction violation detection, has a close match with the timing range of the Mismatch negativity and other ERPs mentioned above. Predictive Coding Framework is applied to Auditory Perception by Friston and extended into Music Cognition by Vuust's research team; thus, it offers a complementary explanation based on Computational Neuroscience [4-5]. Predictive coding suggests that the brain constantly makes high-level predictions at different levels of abstraction regarding sensory input, and then adjusts these predictions based on prediction errors. In terms of music rhythm application for neural networks, it can be regarded as an on-going updating model; Here, beat recognition, pitch determination, meter comprehension and mental expectations need to be processed through the same computing mechanism. The emotional value of prediction errors - whether a violation is surprising, mistaken, or pleasantly unusual in retrospect - depends on multiple factors, such as the listener's pre-existing expectations, their current mood, the music environment at that moment, etc., which are predicted by predictive coding theory.

Koelsch's extensive study on the link between music and emotions provides evidence for neurobiological basis and relationship of emotion elicited by listening to music and anticipation process[6]. It was found by his research that music-elicited emotions involve sub-cortical

structures such as the amygdala, hippocampus and nucleus accumbens, as well as cortical areas involved in higher-order cognitive processing, thus explaining the reason for their simultaneous immediacy and reflection nature, body-cognition integration. In this sense, it can be inferred that there is an internal reason for the generation of electroencephalography response (EEG) in response to violations of patterns, which is not limited to cognitive forecasts of mistakes; rather, they act as elements within the system.

3. Rhythmic Expectation and Emotional Priming

Not merely the series of Sounds occurring at equal time Intervals. It is an active temporal Structure formed by the listener's reconstruction of events, which predicts future sounds and updates it based on subsequent sound inputs. The active creative nature of rhythmic sense perception is precisely this productivity in studying expectations; these brains' forecasts are definite time-bound undertakings that need to be carried out at exactly the right moment and assessed accordingly.

The metric expectation refers to an anticipation at a fixed rate structure; On the contrary, The order-based expectation anticipates the following beat according to one's own experience with rhythm model before, it helps us understand human behaviour and neurons' response to rhythmic deviation respectively. Metric violation, an event that occurs outside of the grid set by previous rhythmic context; Compared to sequential violation, it generates stronger and more automatic neural response, thus supporting the view that metrics are processed more deeply entrained and predicts faster than pattern-based rhythm detection. The difference is embodied in EEG responses and possibly affects the impact of emotional priming on these different types of anticipation about rhythmic sequences differently.

Emotional priming in music Listening is the process by which a person's emotions at this moment influence their understanding and reaction to musical forms. A listener's perception of rhythmic deviations differs when they are in a positive emotional state compared with being negatively or anxiously affected; that is, from the perspective of the brain allocation of predictive resources, the level at which an individual registers a deviation signal, and their overall emotional valuation towards unforeseen situations vary accordingly. According to Nozaradan and others' studies on neural entrainment in response to music rhythm; the brain has an oscillatory-tracking capacity for rhythmic structures under attention modulation and emotion enhancement conditions, thus resulting in varying forms of neuronal entrainment when presented with the same rhythm sequence across different audiences [7]. There are obvious implications for interpreting EEG data from musical Listening Paradigms; That is, Neural Signatures of rhythmic expectation can no longer be distinctly isolated from their Emotional background when making Interpretations.

The relationship of emotional priming and rhythmic expectation is also two-way. Emotional States affect Expectation Processing, and Violations of the Rhythm Generate Emotions which change Subsequent State Expectations. Based on Zatorre and Salimpoorer's researches from 2013 to 2014 showing that the anticipation of musical events may release dopamine through neurochemical pathways; There was an optimal response when expectation was achieved after a long period of expectation[8]. The reward aspect of the musical expectation can refer to the situation where the emotions expressed at specific time nodes in response to rhythmic stimuli are no longer determined by cognitive anticipatory processes but rather due to external motives such as motivational systems prompting individuals to seek rewards, leading us to perceive that music rhythmically activated feelings with positive characteristics because it is intrinsically motivating.

4. EEG Evidence and Neural Signatures

Empirical EEG studies have identified multiple neural indicators with distinct properties and interferences associated with rhythm expectations; They help us understand how the brain assesses, anticipates and responds to such Structures. These markers, although independent events, constitute part of a unified neural system that organises the organisation of hierarchical structure and time-dependent nature in rhythmic anticipation.

Mismatches are among the most studied neurophysiological responses to predictability violations involving sound; They have shown high stability in rhythmic conditions as part of an extensive research project. A type of evoked potential that is mainly generated by the auditory cortex; it appears about 100-250 ms after a deviant sound; It represents an automatic detection response of the brain for deviations from learned expectations [6]. MMN response in time-variant condition is more sensitive to deviation from expected rhythm; The magnitude and latency of the negative ERP components are also influenced by whether there was an existing rhythmic background structure before exposure and how much music participants had prior experience. The MMN amplitude is also affected by emotion; several studies have reported that individuals exhibit larger MMN responses when exposed to stimuli accompanied by intense emotions or changes in rhythm compared to controls or those without emotional stimulation.

N400 activity, initially defined as a marker of semantic processing, has appeared after responses to rhythmic or harmonic deviations in music; This suggests that the two processing systems involved in both languages and music have overlapping neuronal basis for expectation-based synthesis. [6] N400-like responses have been found during rhythmic context; That is, when the rhythmical pattern deviates from expected structurally under the analogy of semantic anomaly in language, it may trigger this mechanism for judging and reacting to expectations breach. For the implication of emotional priming is that, given their close neurochemical basis for rhythm expectation processing and semantic processing; consequently, this modulates emotion in understanding language as observed in cognitive neuroscience research also manifests in rhythmic expectations scenarios.

Oscillatory neural activities at beta and theta frequencies offer an additional means of investigating rhythmic expectations processing; however, Event Related Potentials (ERPs) are insufficient on their own. Beta-band oscillation (BBO), which ranges between 13-30 Hz, is subject to systematic attenuation during rhythmic violation and reoccurrence after an expectation satisfaction; It represents this adjustment and memory update process of predictive expectations through its activity change [7]. Theta oscillations, in the 4-8Hz band, are linked with emotion-memory encoding and recall; their amplitude increases in response to emotionally evocative music pieces, indicating that they may serve as a substrate for emotional priming on rhythmic expectation processing at the level of neuro-oscillatory dynamics.

DEAP, an open multimodal data set containing EEG recordings of 32 people listening to different pieces of music videos accompanied by self-reported valence and arousal ratings, can be used as a benchmark for evaluating how emotions are represented neurologically through brain activity during the listening process; [9] The analysis of DEAP data repeatedly showed that the alpha-band asymmetry, which reflects a difference between left and right frontal activity, correlated positively with the valence of emotions elicited by music; Theta Power Correlated With Arousal Ratings: Thus Establishing That EEG Signatures Of Emotional State During Music Listening Are Reliable And Interpretable In Terms Of Established Dimensions Models Of Emotion. The OpenNeuro repository contains more public-electronic brain recordings from different music-listening experiments, making it possible to study the rhythm-anticipation effect in various listeners with a variety of sounds [10].

Convergence among the above-mentioned EEG findings suggests that there is a pattern of rhythm expectation processing at multiple levels; In other words, automatic prediction error

detection, higher-order structure integration, oscillatory entrainment, and emotional reaction generation work together simultaneously while interacting with each other's roles remain unresolved so far. The emotional priming dimension of this picture is quite essential; that is to say, the conventional cognitive-neuroscience framework of rhythmical anticipation as a prediction-error-minimisation mechanism lacks an account of how emotions modify its parameter values, set the threshold of violation recognition, and attribute different levels of affective value to various neural responses.

5. Discussion

The EEG evidence presented in the previous section shows that there is no clear distinction between rhythmic anticipation and emotional perception as independent systems but rather a continuous process of mutual penetration; Both experiences of music rhythm generation and neural activity recordings exhibit this characteristic feature. These Places' Links have a significant impact on the understanding of music; They may reshape our neural activation networks into one representing reconstruction of emotions-referred-sequence-Response in response to different kinds-of-sensory-stimuli-in-various-modalities.

Predictive coding-based frameworks provide a more theoretical basis for these phenomena' observation; However, in practice, they need to be adjusted to better reflect the emotion-attribute Rhythm anticipation mentioned by electroencephalography research [4][5]. The standard Predictive Coding account treats the prediction errors' signal predictions as emotion-Neutral Information but does not contain any Emotional Valuation. Based on the evidence reviewed in this article, it can be inferred that in music rhythm situations, predictions' errors are not emotionally indifferent; Rather, they have valences based on listeners' previous emotions, musical environments, and motivational values for anticipated events as proposed by Huron's Integrated Touchpoint-Response Analysis theory at its start point but which still lack an all-encompassing framework to explain these phenomena fully yet thoroughly.

For the purpose of research on music therapy and emotional management, the results are still relatively unpayable attention in this field. Based on the way that EMG evidence indicates rhythmic anticipation processing is related to emotions; Then deliberately alter rhythmic anticipation - through syncopation, temporal shift or tempo variations - can be seen as an effective tool for emotion regulation at present, and its underlying neurological mechanism has been sufficiently elucidated to support more theoretical applications. There is a lack of reliable evidence due to the limited extent and ecological invalidity in the application setting of most studies on EEG-Music Cognition; The relationship between laboratory EEG data and the neural changes during actual listening remains unclarified so far[2].

6. Conclusion

The brain waiting for the beat is not only an Event-Timekeeper but also reacts to whether rhythmic events have arrived. An active predictor and emotion-driven system that creates a pre-warned state with anticipation before arriving at every music scene; It responds in real-time to the success or failure of performance based on both cognition, emotions and motivations. In these reviews, EEG signatures such as Mismatch Negativity, N400, Beta Suppression, Theta Entersion and Alpha Asymmetry cannot be viewed as individual neuronevents but rather manifestations of a whole-system organisation that demonstrates fundamental prediction-orientation and emotional saturation at its core.

Finally, this problem remains unexplored: The changes in the neural basis with respect to real-time music appreciation; Which role does personal differences due to emotional conditioning history have on musical rhythm expectation formation; And whether the findings apply to various contexts under different conditions of daily life listening. These are questions about a

research program currently under way, which will be provided with more advanced neuroimaging methods as well as richer public data resources; It supports the formulation of testable prediction hypotheses in the field of predictive coding theory, without restricting itself to simple theories.

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