UNIVERSITY OF PAVIA – IUSS SCHOOL FOR ADVANCED STUDIES PAVIA

Department of Brain and Behavioral Sciences (DBBS)
MSc in Psychology, Neuroscience and Human Sciences

The Effect of Rhythmic Complexity on Groove

Supervisors:
Prof. Carlotta Lega

Prof. Laura Ferreri

Thesis written by
Eshita Sharma

513341

Academic year 2024

ACKNOWLEDGEMENTS

I would like to extend my deepest gratitude to my supervisors, Prof. Carlotta Lega and Prof. Laura Ferreri. Thank you for giving me the opportunity to be part of the lab, and I hope to carry the knowledge and insights you have shared with me into my future research. I am also incredibly thankful to everyone at the MusiCognition Lab in Pavia for their unwavering support over the past two years. Your kindness has been invaluable.

A heartfelt thank you to my family for always listening and believing in me. To Himani, Kashika, Kanishk, and Keshab, I am truly grateful for your understanding and constant support. To Chloe, Jamie, Francesca, and Shreya, thank you for making Pavia a place I will always hold dear.

Lastly, here's a background playlist to accompany you as you read this thesis: Spotify Playlist.

CONTENTS

1. ABSTRACT

Music instantly captivates listeners' attention, provides pleasure, motivates movement, and promotes social interaction. Groove refers to the pleasurable urge to move to music, engaging both sensorimotor and reward domains. Listening to and moving to rhythm can elicit a variety of pleasurable emotions, with rhythmic complexity influencing these responses. Many studies show that rhythms of medium complexity, which balance predictability and uncertainty, enhance pleasure and motivation to move.

The current study sought to assess the relationship between rhythmic complexity and groove using the stimuli taken from the Computerized Adapted Beat Alignment Test (CA-BAT), a comprehensive tool for testing musical beat-processing abilities. Specifically, we explored how varying levels of rhythmic complexity in the CA-BAT musical stimuli influenced Pleasure and Wanting to Move. In addition, we investigated whether individual differences in musical reward sensitivity and musical training affected this relationship. The study involved 120 participants who rated 25 musical excerpts from the CA-BAT on a five-point scale for pleasure and wanting to move. We also collected data on musical reward sensitivity using the extended version of the Barcelona Musical Reward Questionnaire (eBMRQ) and assessed musical training using subscales of the Gold-MSI to explore their potential influence on the observed effects.

Using pulse entropy as a predictor for rhythmic complexity, we observed an inverted U-shaped relationship with both Pleasure and Wanting to move ratings. This pattern supports the idea that the CA-BAT stimuli follow an inverted U shape for groove, reinforcing that medium-complexity rhythms enhance pleasure and the motivation to move. When we included the eBMRQ score and its subscales to assess the impact of musical reward sensitivity, we found that the SensoryMotor and Social subscales significantly influenced groove ratings. However, musical training did not have a significant effect on either Pleasure or Wanting to move. These findings suggest that groove is closely tied to perceived rhythmic complexity and underscore the intricate ways in which individual differences in musical reward interact with rhythmic patterns to shape the sensation of groove.

Keywords: Groove, Rhythmic Complexity, Musical Reward, CA-BAT

2. INTRODUCTION

People intuitively respond to music by moving to the beat, demonstrating the link between movement and music. One does not have to go far to see the importance of music and movement in our lives. Infants demonstrate sensitivity to rhythmic patterns in music as early as 7 months of age (Phillips-Silver & Trainor, 2005). This could be due to the intrinsically rewarding quality of music. It instantly attracts our attention, gives us pleasure, encourages movement, and promotes a sense of community with others. These combined musical experiences correspond to the concept of "groove," which is a person's desire to move in response to music, accompanied by a sense of pleasure (Madison 2001, 2006; Janata et al., 2012).

The most important musical quality that influences groove is rhythmic complexity (Chen et al. 2008; Repp and Su 2013; Witek et al., 2014). Syncopation is one of the most studied forms of rhythmic complexity in music, defined as a rhythmic event that deviates from listeners' metric expectations (Fitch & Rosenfeld 2007; Ladinig et al., 2009; Longuet-Higgins & Lee 1984; Margulis & Beatty 2008; Song et al., 2013; Temperley, 2010; Witek et al., 2014). Additionally, there is an inverted U-shaped relationship between the degree of syncopation and groove, where a moderate amount of syncopation should result in the highest level of groove (Witek et al., 2014). In simple terms, even though the rhythm is not simple, groove makes us want to move to music because it feels good. Moreover, the syncopations in music produce gaps that invite the body to fill in. When the groove incorporates syncopation, the meter becomes acoustically incomplete. This encourages the listener's body to become the most immediate and tangible means by which the meter can be filled (Witek, 2016).

Over the last two decades, there has been an increase in groove research. Several fields have focused on groove in recent decades, most notably ethnomusicology, musicology, psychology, and neuroscience. The majority of studies encompass various aspects, including understanding the concept of groove, musical features associated with the groove experience, body movement during groove, neurophysiological activity during groove, characteristics of listeners that impact the groove experience, and the influence of culture and environment on the groove experience (Etani et al., 2024).

The relationship between groove experience and rhythm complexity, while already an active area of research, requires further exploration. In particular, few studies in literature used complex and naturalistic musical stimuli to study the relation between groove sensation and rhythm complexity. Furthermore, while some studies of the syncopation-groove relationship have reported group differences related to experience (e.g., musical or dance training), no studies have investigated whether individual differences in musical reward affect groove perception. Thus, the aim of this dissertation is to investigate the effects of

(a) syncopation on groove across the naturalistic musical stimuli of the Computerised Beat Alignment Test (CA-BAT) and;

(b) the impact of the level of reward sensitivity and musical practice on groove.

The hypothesis is stated as the pleasure and wanting to move ratings would follow an inverted U shaped curve across different levels of pulse entropy for the CA-BAT stimuli. Additionally, the groove ratings would be influenced by the eBMRQ scores and Musical Training. The details of sample participation, methodology, together with stimuli and tools used are elaborated upon. Following this, the procedure for the entire experiment will be detailed. The data analysis and results will be presented following the procedure to arrive at the conclusions. Finally, a discussion of the data acquired within the current literature will be presented, along with the appropriate conclusions.

3. BACKGROUND

3.1 MUSIC AND REWARD

Music has the power to deeply affect us. It is highly valued in people's lives and is not interchangeable like other primary and secondary rewards such as food or money. The value of music is not determined by the tangible rewards it provides, but by its intrinsic worth. Music is not simply a means of achieving rewards, but rather an independent source of reward. Understanding why music is rewarding to us is linked to the broader discussion of whether music evokes genuine emotions and the mechanisms behind this process. Overall, enjoying music increases arousal, emotional communication, and contagion (Zald & Zattore, 2011). Furthermore, music rewards can be explained by the rewards linked to expectancy and prediction confirmation (Zald & Zattore, 2011). This hypothesis proposes that the pleasure gained from music stems from the way the brains process and anticipate sequential occurrences, rather than from the direct induction of certain emotional states.

According to Leonard Meyer in his book "Emotion and Meaning in Music" (1956), music's ability to evoke emotion comes from our expectations. David Huron's "Sweet Anticipation" (2006) expands on this idea and introduces five components (ITPRA) that connect expectations in music to reward:

- *Imagining responses:* This happens when we mentally complete music before it actually ends.
- *Tension responses:* It comprises the preparation, both physical and mental, that occurs in anticipation of the next step or resolution in music.

- *Prediction responses:* This involves comparing the prediction with the actual outcome of the music. If the prediction is accurate, it is experienced as rewarding.
- *Reaction responses:* It refers to the quick response to the actual outcome, whether positive or negative.
- *Appraisal responses:* It indicates the conscious determination of the meaning of the outcome.

3.1.1 MUSICAL REWARD AND RHYTHM

Music is a universal cultural practice found in diverse forms around the world (Brown & Jordania, 2013; Mehr et al., 2019; Savage et al., 2015). Furthermore, the environment around us is full of auditory stimuli that follow recurring and temporally consistent patterns. Humans can easily process rhythmic information from a wide range of sound sources with variable levels of rhythmicity.

Rhythm is the structuring of sounds and silences over time, including patterns of length and inter-onset interval. In music, these patterns aid in the perception of an underlying beat, eliciting natural physical responses (e.g., clapping), as well as the recognition of hierarchical timing structures within a metrical framework, contributing to the cognitive concept of meter (London, 2012; McAuley, 2010). Emotional aspects in music are inextricably linked to its rhythmic characteristics (Trost et al., 2017), an attribute that is commonplace across cultures and in daily life due to its universal appeal. Rhythm, particularly the possibility for rhythmic entrainment based on certain patterns, appears to play an important role in eliciting emotional responses through music.

Rhythm is strongly linked to our cognitive and affective processes. The temporal structures of music have been proposed to cause musical emotion via altering physiological entrainment processes such as heart rate and respiration (Juslin, 2013; Trost & Vuilleumier, 2013). Music's rhythmic qualities, such as perceived complexity and syncopation, can influence subjective emotional ratings such as valence, arousal, and enjoyment (Gabrielsson & Lindström, 2010; Gundlach, 1935; Keller & Schubert, 2011). Moreover, studies have demonstrated that rhythm can increase arousal and encourage emotions of connectedness (Juslin, 2013; Juslin et al., 1993; Trost et al., 2017), both of which are intimately related to reward processes, as hypothesized by Zatorre (2015). While musical reward is an important component of emotional experiences in music (Goupil & Aucouturier, 2019), the relationship between rhythm, music, and reward has lately emerged as a topic of discussion (e.g., Matthews et al., 2020; Stupacher et al., 2022; Witek, 2016).

There is a significant relationship between rhythmic expectancy and music reward, which appears to be reinforced neurally via dopaminergic reward-motor circuits. At the neurological level, rhythm processing has been linked to a large network of brain regions, including the basal ganglia, cerebellum, premotor cortex, and supplementary motor area (Grahn, 2012). Furthermore, the basal ganglia, particularly the dorsal structures of the striatum (i.e., the putamen and caudate nucleus), emerge as central regions and primary neural correlates of beat perception (Grahn, 2009; Nozaradan et al., 2017; Teki et al., 2011; Thaut et al., 2008) and interval timing (along with the cerebellum), and they also show strong links to the reward system (Buhusi & Meck, 2005). On a neurochemical level, dopaminergic transmission has been shown to cause music reward hedonic and motivational responses (Ferreri et al., 2019). Hence, reward responses to rhythm may thus be related to the strong temporal expectations created by musical rhythm.

The pleasure we derive from music and its emotional impact may stem from predicting musical events, encountering surprises or deviations from our expectations (i.e. through rhythm manipulation), and the tension and release patterns caused by errors in prediction and fulfillment. As follows, synchronization/entertainment is one of the most notable interactions between the listener and external rhythmic information. The rhythmic information gathered from the external musical signal interacts with the listener's internal states, improving the temporal coordination of actions with external rhythmic events (also known as sensorimotor synchronization) (Fiveash et al., 2023). This process can be defined as the coupling of internal oscillations (or other endogenous timekeeper mechanisms) with the periodicity perceived in the external rhythm, such as the musical beat or meter (Fiveash et al., 2023). The emotional characteristics evoked by rhythm seem to influence entrainment; for example, pleasant music induces entrainment at a finer rhythmical level than unpleasant music (Trost et al., 2014). Furthermore, reward responses are tightly associated with movement through sensorimotor synchronization, physical entrainment, and groove. As a result, studies on groove experience show a strong link between rhythm, movement, prediction, and pleasure (Janata et al., 2012; Matthews et al., 2020; Vuust & Witek, 2014; Witek et al., 2014).

In a nutshell, the link between rhythm and reward is strongly connected due to rhythm's ability to induce movement. Moreover, psychometric measures designed to assess individual differences in reward sensitivity might be used to further explore the relationship between rhythm and musical reward. One such tool is the Barcelona Music Reward Questionnaire (BMRQ, Mas-Herrero et al., 2012). The BMRQ is a reliable tool for measuring musical reward, as it is associated with both psychophysiological and neural responses (Ferreri et al., 2019; Martínez-Molina et al., 2016; Mas-Herrero et al., 2014).

The BMRQ evaluates people's sensitivity to music reward (musical hedonia) by analyzing different facets of their musical experience. The sensory-motor subscale is strongly linked with other subscales related to musical pleasure (e.g., emotion evocation, mood regulation, musical seeking, and social reward experience). It contributes significantly to the complex reward experience during music listening. The sensory-motor subscale specifically measures the capacity to spontaneously and intuitively synchronize body movements to a rhythmic beat utilizing simple or complex actions (for example, toe-tapping to dancing). This necessitates the integration of somatosensory-motor brain networks with auditory processing networks (Mas-Herrero et al., 2012). Ultimately, the tool represents a crucial asset in comprehending the intricate relationship between rhythm and reward, along with its implications for human cognitive and social mechanisms.

3.2 GROOVE

Music is often associated with the sense of hearing, however, while experiencing music, such as at a live concert or a ritual, it is apparent that the process causes the performers or the audience to respond physically by moving their bodies, such as swaying or dancing. This suggests that our musical experience is more than just auditory, but also multisensory and embodied, involving our entire self (Bowman, 2000; Leman & Maes, 2015; Russo, 2018). When we listen to music, it's natural for us to move our bodies in rhythm to the beat, such as tapping our feet or nodding our heads, - a response that's hard to resist (Gonzalez-Sanchez et al., 2018; Zelechowska et al., 2020). This innate need to tap or move to the rhythm has resulted in the study of "groove," which refers to the pleasurable urge to move to music. (Janata et al., 2012; Witek et al., 2014).

The term "groove" has long been identified with music from the African American and Cuban diasporas. Music genres such as funk, hip-hop, jazz, and Afro-Cuban music are considered "groove-based." Musicians frequently use the term to describe a rhythmic section or the sensation of being linked as a group while playing. The psychological concept of groove is wider than Western popular music. It applies to every scenario in which music triggers bodily movement, independent of style or cultural background (Pressing, 2002). Since music is used for dancing in the majority of cultures (Kaeppler, 2000; Nettl, 1999), it is not surprising that there are concepts similar to groove in several languages, such as "balanço" in Brazilian, "nori" in Japanese, or "lüpfig" in Swiss German (Senn et al., 2019). In recent decades, "groove" has been operationally defined as the "pleasurable desire to move to music" (Madison, 2006; Janata et al., 2012).

The study of groove gained traction with the work of musicologist Charles Keil in 1987. Keil and Feld (1994) stressed the significance of "participatory discrepancies" in timing, pitch, timbre, and other groove-related elements. While groove research originated in the humanities, particularly musicology, ethnomusicology, and philosophy, with a focus on microtiming analyzed through rigorous examination and interviews with musicians, empirical groove research has recently expanded, particularly in the fields of psychology and neuroscience.

3.2.1 The Link between Groove and the Brain

The term "groove" is frequently used to describe the strong connection between music and the human body. When we listen to music and feel compelled to move our bodies to the rhythm, we refer to the performance as having a "groove." The link between feeling a groove and moving our body while listening to music emphasizes the relevance of the sensorimotor component in this phenomenon. Furthermore, when we experience a groove, we feel pleasure, demonstrating that reward plays an important part in this interaction.

In a study using Transcranial Magnetic Stimulation (TMS), Stupacher et al. (2013) found that music associated with a high-groove experience activated the motor cortex more than low-groove music, even when no overt movements were present. Similarly, in a functional magnetic resonance imaging (fMRI) experiment, Matthews et al. (2020) measured brain activity in response to high and low-groove stimuli and reported stronger activation in the motor and reward-related areas (putamen, supplementary motor area, nucleus accumbens, caudate, and orbitofrontal cortex), as well as in prefrontal and parietal cortices associated with the groove experience. Using functional near-infrared spectroscopy (fNIRS), Fukuie et al. (2022) investigated the role of the dorsolateral prefrontal cortex (DLPFC) in inhibiting executive functions associated with the groove experience. Participants completed a Stroop task before and after listening to a metronome or groove-related rhythms. While there was no overall difference between conditions, subgroup analysis revealed that familiarity with groove rhythms was associated with enhanced DLPFC activity and linked with better inhibition of movement execution. Thus, groove research has the potential to expand the understanding of sensorimotor interaction in terms of its significance to motivation and learning.

3.3 COMPONENTS OF GROOVE

Music processing in the brain, including the perception of melody, harmony, and rhythm, has typically been examined as an auditory phenomenon using passive listening paradigms. However, when we listen to music, we actively anticipate what will happen next. This active involvement has resulted in an improved understanding of music processing, which includes brain areas associated with action, emotion, and learning. The current body of evidence supports the definition of groove as "the pleasurable sensation of wanting to move the body to music," emphasizing both the "movement-inducing" and "pleasurable" aspects (Janata et al., 2012; Matthews et al., 2019; Stupacher et al., 2022; Vuust et al., 2022; Witek et al., 2014, 2020). Furthermore, because both movement induction and pleasure experiences include dopamine release (Gebauer et al., 2012), they are most likely linked rather than independent of one another. Thus, the two basic components of the groove are as follows:

- ***Pleasure***

Meyer's pioneering work (1956) made it evident that music anticipation can elicit a wide range of complex emotional responses, including awe, surprise, and discomfort, as well as laughing, foot tapping, singing, tears, and a lump in the throat (Huron, 2006). It can cause psychogenic responses such as 'shivers down the spine', elevated heart rate, and perspiration (Rickard, 2004).

The pleasure associated with groove can be attributed to various elements: music (syncopation and the formation of expectancies) (Witek et al., 2014; Salimpoor et al., 2011, 2015), immersion (experiencing a state akin to flow) (Csikszentmihalyi, 1988), movement (reduction of prediction error in rhythm perception and the triggering of neurohormonal systems) (Vuust & Witek, 2014; Tarr et al., 2014), and social interaction (collaboration, affiliation, and social bonding) (Savage et al., 2020). These types of pleasure act at the neurological, psychological, behavioral, and social levels, respectively.

- ***Wanting to Move***

Humans are already sensitive to groove at a young age (Janata et al. 2012). Groove is associated with increased music engagement, spontaneous rhythm synchronization, and improved rhythm and beat perception (Etani et al., 2024). Moving to the beat (and reproducing body movement) is most likely motivated by the pleasure (i.e., reward) resulting from prediction confirmation and learning. Furthermore, Matthews et al. (2022) showed that subjective perception of synchrony is more strongly associated with groove assessments than objectively measured synchrony. Additionally, this association is strongest in rhythms with modest syncopation (Witek et al., 2014; Stupacher et al., 2022; Matthews et al., 2019). The groove experience has a deep association with body movement, indicating bidirectional ties between perception and action (Etani et al., 2024).

3.4 MECHANISMS OF GROOVE

- ***Dynamic Attending Theory***

According to dynamic attending theory (DAT), attention is allocated through endogenous oscillations whose peaks become aligned with relevant stimuli in the environment for enhanced processing, while less relevant stimuli in troughs are processed more poorly (Jones, 1976; Jones & Boltz, 1989; Large & Jones, 1999). This theory has been expanded in cognitive neuroscience, where entrained oscillations have been envisioned as a mechanism of attentional selection (Lakatos et al., 2008, 2013), controlling the gain of sensory neurons by aligning excitatory phases of neural populations with the timing of external stimuli for more fluent processing (Nobre & Van Ede, 2017; Obleser & Kayser, 2019).

- ***Neural Resonance Theory***

According to the "neural resonance" theory, beat perception occurs when nonlinear oscillations in the nervous system synchronize with external rhythmic stimuli. According to Large and Snyder (2009): "Non-linear oscillations are ubiquitous in brain dynamics and the theory asserts that some neural oscillations -perhaps in distributed cortical and subcortical areas - entrain to the rhythms of auditory sequences."

- ***Theory of Embodied Cognition***

Embodied cognition is the theory that the body (sensations and bodily experiences) is necessary for our comprehension of the world, conceptual knowledge production, and meaning formation (Fincher-Kiefer, 2019; Leman & Maes, 2015; Varela et al., 2017). According to Leman and Maes (2015), one method to emphasize the relevance of embodiment in music perception is to demonstrate that embodiment is more than just the influence of music on action; rather, the effect of action on music perception is critical in making meaning of music. It highlights the bi-directionality of the linkages between perception and action: on one hand, perceiving beats require the covert imitation of body movement, and on the other hand, outwardly moving to the beat promotes rhythm and beat perception (Shapiro, 2019).

- ***Predictive Coding of Music***

According to the predictive coding of music (PCM) paradigm, when we listen to music that has melody, harmony, and rhythm, the brain uses a predictive model based on prior experience to direct our perception (Vuust & Witek, 2014). The PCM model posits that music perception, action, emotion, and learning are recursive Bayesian processes in which the brain tries to reduce prediction error (Vuust & Frith, 2008), as formalized in enactive forms of predictive processing (also called active inference). A prediction error is a quantity used in predictive coding to represent the difference between an observation or point estimate and the predicted value. Predictive coding updates expectations (to generate predictions) based on precision-weighted prediction errors. As a result, the processes underpinning music perception and action are linked, so that perception lowers prediction error by updating predictions, whilst action reduces prediction error by generating predicted sensory signals. Emotion, attention, and motivation serve as Bayes optimum biases to contextualize prediction, directing behavior, action, and learning (Vuust et al., 2022). For example, rhythm perception could be viewed as follows: the brain estimates the error between bottom-up rhythmic input and top-down model predictions in the brain. The recursive update of the model, or the generation of movements that reduce the prediction error, will aid in rhythm perception. On this account, rhythms with moderate levels of syncopation elicit the groove experience the most strongly because they maximize the weighted prediction error (the product of prediction error and precision), causing the listener to reduce this error by moving, for example, tapping the foot (Elst et al., 2021; Koelsch et al., 2019; Stupacher et al., 2022;

Vuust et al., 2018, 2022, 2009; Vuust & Witek, 2014) (See, *3.5.2 Predictive Coding and Rhythmic Complexity*.) This active listening process underpins emotional responses to music and musical learning, as well as the long-term updating of our underlying prediction model. Music is thus an effective instrument for studying the predictive brain because of the way its structure encourages anticipation.

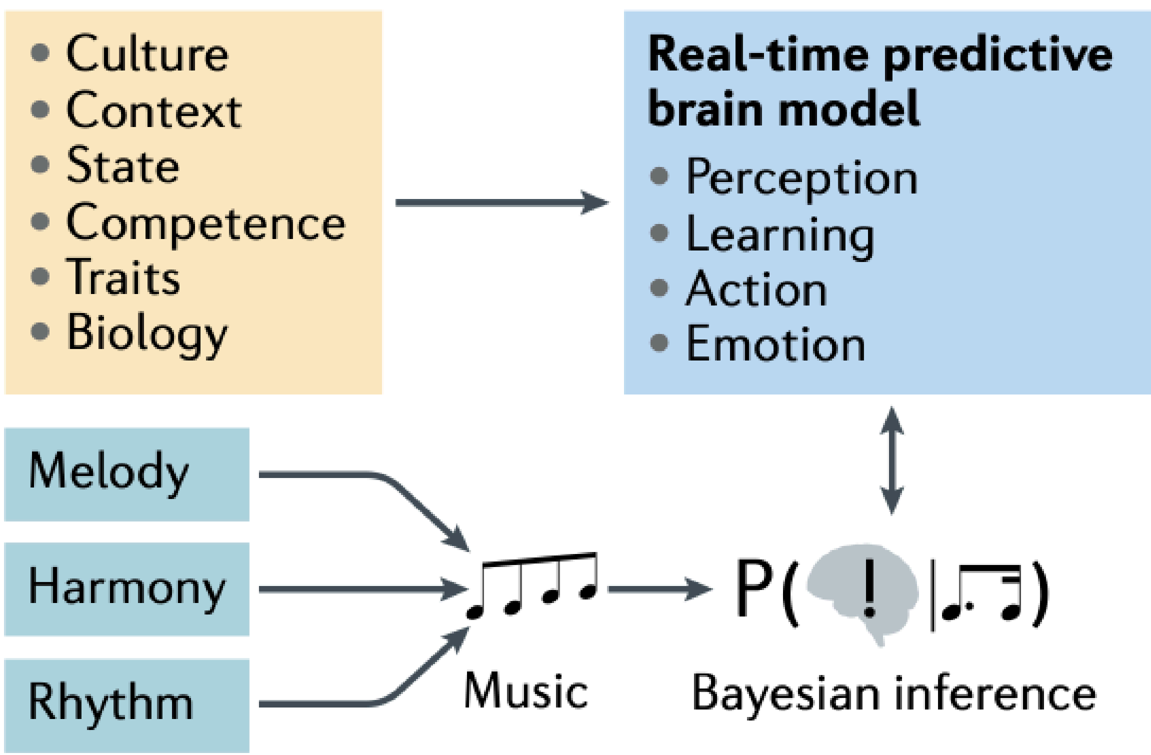


Fig 1: Predictive Coding of Music (PCM) Model: The brain's real-time predictive (generative) model (indicated with an exclamation point) guides music perception and is influenced by prior experience. The predictive model is based on cultural background, musical competency, current

context, brain state, including attentional and emotional states, personality attributes, and innate biological components. The brain is continually attempting to minimize prediction error at all levels of the brain hierarchy via Bayesian inference. Adapted from Vuust et al. (2022).

- ***Psychological Groove Model***

Senn et al. (2019) presented a model that offers a comprehensive understanding of the psychological mechanisms underlying the groove experience. According to the model, the desire to move in response to music is impacted by an inner representation of the music's timing, an interest in the music's timing, pleasure from listening, and a feeling of energization. The authors additionally address the three types of feedback: sensory, hedonic, and energetic. These sorts of feedback are associated with the desire to move, pleasure, and energy arousal. In this framework, they proposed that the groove experience is linked to musical elements that elicit temporal regularities and time-related interest. The groove model (Senn et al., 2019) places the impulse to move and entrained body movement in the center and as the outcome (known as groove experiences). Several researchers have linked groove to the experience of movement (Janata et al., 2012; Stupacher et al., 2013; Ross et al., 2016). Moreover, many studies (Madison, 2006; Janata et al., 2012; Witek et al., 2014; and Matthews et al., 2020) consider pleasure to be a fundamental aspect of perceiving the groove. In fact, the Experience of Groove Questionnaire contains two major dimensions: the desire to move and pleasure (Senn et al., 2020). The model also considers the influence of individual backgrounds (e.g., musical expertise, perceptual and motor abilities) and listening conditions (e.g., live or recorded music), which can explain the bulk of groove empirical study outcomes.

3.5 FEATURES OF MUSIC CAUSING GROOVE

Not every music moves us. Music uses a variety of components to make it engaging. However, not all music inspires us to move our bodies, which begs the issue of why. In a classic study, Berlyne (1973) claimed that an inverted U-shaped curve (also known as the Wundt curve) (Wundt, 1874), represents a general relationship between aesthetic appreciation and structural complexity in art. According to this relationship, increasing complexity corresponds positively with liking, arousal, and enjoyment until an optimal point is reached, after which the effect reverses. Heyduk (1975) was the first to empirically establish this theory for music, and it was then applied to subjective complexity assessments in popular music (North & Hargreaves, 1995, 1997, 1998). However, the appropriate level of complexity varies according to musical context (North & Hargreaves, 1997), personality (McNamara & Ballard, 1999), genre, and listening preferences (Orr & Ohlsson, 2005). Additionally, culture is expected to regulate emotional responses to complexity in music, as complexity levels and expressions vary between cultures (Hannon et al., 2012; Roncaglia-Denissen et al., 2013).

Rhythmic elements such as syncopation, microtiming, tempo, beat salience, and event density, as well as acoustic features like harmonic complexity and bass sounds, have been demonstrated to influence the groove experience (Etani et al., 2024). Notably, the experienced groove is also rated differently based on the musical style that reflects the musical features. Furthermore, the groove experience was found to be altered not only by auditory but also by tactile and visual stimuli. (Etani et al, 2024).

The empirical research on groove has focused on musical properties that may influence the groove experience. Some studies have investigated qualities that add interest to music, such as syncopation (Sioros et al., 2014; Witek et al., 2014), rhythmic variability (Wesolowski & Hofmann, 2016), microtiming (Davies et al., 2013; Frühauf et al., 2013; Senn et al., 2016), or the interaction of rhythmic and harmonic complexity (Matthews et al., 2019). Additional studies focused on meter qualities that promote regularity, such as beat salience (Madison et al., 2011) and tempo (Etani et al., 2018). Moreover, the listeners' backgrounds, such as musical taste or familiarity with the repertoire, have also been demonstrated to influence the groove experience (Janata et al., 2012; Senn et al., 2018, 2019). Among the aforementioned, the relationship between groove experience and syncopation is an ongoing field of research in neuromusic science.

3.5.1 RHYTHMIC COMPLEXITY / SYNCOPATION

Syncopation is described as "the weight of a given note or rest is the level of the highest unit that it initiates" (Longuet-Higgins & Lee, 1984), or more broadly as "rhythmic event that violates listeners' metric expectations" (Witek et al., 2014). Most music is arranged around an abstract metrical structural framework made up of strong (accented or stressed) and weak (unaccented) events that occur at regular intervals (Handel, 1989). Rhythmic, melodic, and harmonic patterns are placed on the underlying metrical framework. A rhythmic pattern with strong accents that correspond to the strong locations of the metrical framework is referred to as unsyncopated, or "with the beat." In contrast, a rhythmic pattern in which accented or strong events are inserted in weak positions in the underlying metrical structure is referred to as syncopated or "off beat." As a result, syncopated rhythms emphasize some weak points in the metrical structure while leaving surrounding strong spots "empty," or without stress. Syncopated rhythms are among the most popular rhythms across various musical cultures and idioms (Toussaint, 2019). Syncopation is thus an effective musical tool for creating music that listeners can move to and take pleasure in.

Accounting that although syncopation is one of many forms of rhythmic complexity (Longuet-Higgins & Lee, 1984; Fitch & Rosenfeld, 2007), it appears to be the most appropriate predictor of perceived rhythmic complexity; Thul and Toussaint (2008) "found that measures of syncopation outperformed other measures in explaining the behavioral data" from judgments regarding perceptual, metric, and performance complexity of rhythm. Syncopation models were found to better explain the variability in these assessments than standard deviation and entropy (i.e., the degree of uncertainty in a random sample, from an information theory perspective) (Witek et al., 2014). Furthermore, syncopation seems to be the most "important structural factor in embodied and affective responses to groove" (Witek et al., 2014).

3.5.2 Predictive Coding and Rhythmic Complexity

The theory of predictive coding of rhythmic incongruity (PCRI) aims to explain the universal sensation of groove as a result of rhythmic complexity. It implies that modest levels of rhythmic complexity provide enough prediction errors to challenge our internal sense of the rhythmic structure while not fully disrupting it. In these situations, we have a strong desire to move to suppress these expected errors and improve our internal rhythmic model using a technique called active inference. At both low and high levels of rhythmic complexity, there are either insufficient prediction errors to require movement or too many prediction errors to perceive a coherent pattern upon which to base the way we move. As a result, the tendency to move to music is predicted to follow an inverted U-shaped curve dependent on rhythmic complexity (Witek et al., 2014; Stupacher et al., 2022; Matthews et al., 2019).

More comprehensively, according to PC, rhythm perception can be regarded in the following way: the brain calculates the error between bottom-up rhythmic information input and top-down model predictions. The recursive update of the model, or the development of movements that reduce the prediction error, will aid in rhythm perception. On this account, rhythms with moderate levels of syncopation elicit the groove experience the most strongly because they maximize the weighted prediction error, causing the listener to reduce this error by moving (Elst et al., 2021; Koelsch et al., 2019; Stupacher et al., 2022; Vuust et al., 2018, 2022, 2009; Vuust & Witek, 2014).

In simple terms, the weighted prediction error is calculated by multiplying the difference between the expected and actual stimulus (prediction error) by the reliability of the prediction (precision) (Fig. 2). For example, rhythms with minimal syncopation lead to minor prediction errors, whereas rhythms with significant syncopation diminish the accuracy of the predictive model, resulting in minimal weighted prediction errors in both cases. On the other hand, rhythms with moderate syncopation lead to moderate levels of both prediction error and precision, resulting in a substantial weighted prediction error. Consequently, when listening to rhythms with moderate syncopation, individuals aim to minimize the weighted prediction error more compared to rhythms with low and high syncopation. One way to achieve this is by moving the body to reduce precision. By moving the body, the prediction differences can be overlooked by reducing the sensory precision. The inclination to move the body to rhythms with moderate syncopation (feeling the groove) emerges as it drives us to lessen the weighted prediction error by decreasing the precision of sensory information.

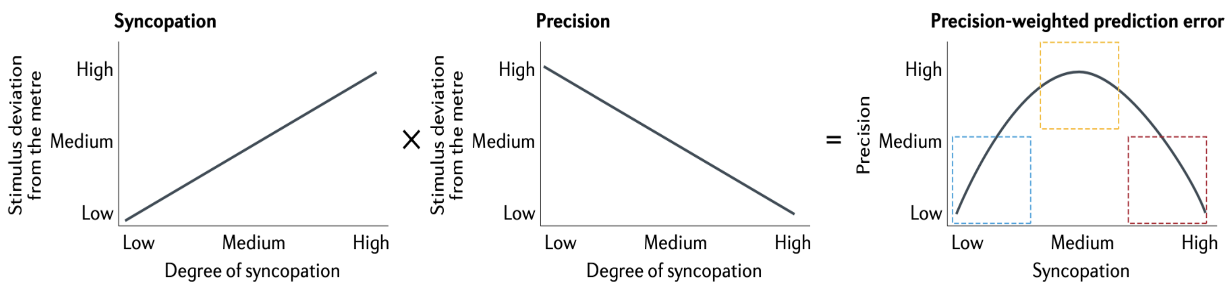


Fig 2: Explaining the inverted U-shaped relationship between the groove experience and the degree of syncopation by predictive coding. Adapted from Vuust et al. (2022).

Witek et al. (2014) investigated the relationship between groove experience and degree of syncopation and discovered an inverted U-shaped relationship between groove ratings and a computational index of syncopation (calculated using a procedure based on work by Longuet-Higgins & Lee, 1984). This study reveals that rhythms with medium syncopation produce the most intense groove sensation. As Matthews et al. (2022) noted, rhythms with medium syncopation are presumably complex enough to reduce uncertainty (violates expectation), but not so complicated that they limit learning (predictability). As a result, beats with medium syncopation would moderately breach expectations, eliciting "sweet anticipation" (Huron, 2008; Stupacher et al., 2022).

3.5.3 Rhythmic Complexity, Groove, and Reward

According to theories on pleasure and expectations, medium complexity rhythms (as opposed to low and high complexity rhythms) increase pleasure and desire to move by providing a balance of predictability and uncertainty (Vuust & Witek, 2014; Witek et al., 2014). Thus, listening to and moving to rhythm can evoke a wide range of positive emotions, both affective and pleasurable, and the complexity of the rhythm influences these responses (Stupacher et al., 2022). The fact that rhythms of intermediate complexity are perceived as more pleasurable (Kraus & Hesselmann, 2021; Vuust & Witek, 2014) may reflect a domain-wide feature of statistical inference learning: optimal learning rates are obtained for intermediate stimulus complexity, which is thus more valued (Erle et al., 2017). This demonstrates that the hedonic part of music may be derived from generic systems that link prediction and reward.

The inverted U-shaped link between syncopation and groove experience has been replicated using physiological measures such as pupillometry (Bowling et al., 2019; Spiech, Sioros, Endestad, Danielsen, & Laeng, 2022) and independent of culture and rhythmic ability (Witek et al., 2020). It has been evaluated for rhythm and groove in both within- and between-culture contexts (Witek et al., 2020, 2014; Matthews et al., 2019), and it is influenced by musical expertise (Matthews et al., 2019). Optimal levels of the pleasurable sensation of wanting to move have recently been linked to neural activity in the brain's motor and pleasure networks

(Matthews et al., 2020), and can thus be seen as a result of precision-weighted prediction error arising from a discrepancy between the syncopation in the auditory input and the motor system's inclination for isochronism (Vuust et al., 2018, Large et al., 2015). Importantly, optimal groove experience has been associated with activity in the nucleus accumbens (NAcc) and orbitofrontal cortex, two critical parts of the reward network that are highly sensitive to the predictability of action outcomes (Matthews et al., 2020). Ultimately, syncopation is a common form of complexity in music connected with groove, and positive affect in groove is associated with a desire for body movement, making it a viable choice for understanding the link between pleasure, desire for movement, and groove.

3.5.4 Pulse Entropy

Entropy is defined as the expected surprise or information content (also known as self-information). In other terms, it is the predicted or average predictability of a random variable (for example, an upcoming occurrence). It is a measure of disorder and unpredictability. Entropy in a communication system refers to the quantity of information contained in a message. The more disorganized, or unpredictable, communications become, the more difficult they are to transmit. Many systems can be seen via the lens of information theory, including text messages, communication lines, and spoken languages. Manzara et al. (1992) found that music can also be examined usefully from this perspective.

Humans tend to synchronize their movements with the primary pulse of the music, which is known as the meter. The meter is composed of variably accented groupings and subdivisions of that pulse and can be conceptualized as a predictive model (see Fig. 2). Pulse Entropy measures the degree of syncopation in a metric rhythm. It stands in contrast with pulse clarity, which measures how easily listeners can detect the underlying pulsation in music. This comprehension of music appears to play an important role in distinguishing musical genres, allowing for better differentiation across genres with similar average tempos but differing in the degree of development of the dominant pulsation over the rhythmic texture.

In the context of musical groove, individuals may feel compelled to move the body to a regular metrical rhythm, at least on a subpersonal level, to suppress or reduce the precision of prediction errors caused by syncopations. Therefore, as the level of syncopation, or pulse entropy, increases in a groovy rhythm, the accuracy of the beat decreases. This is evidenced by a decline in sensorimotor synchronization in response to heightened syncopation, as observed in tapping and motion capture studies of musical groove (Repp & Su, 2013; Witek et al., 2017). This implies that the internal metrical model does not align with the sensory input for the most complex levels of syncopation. In contrast, at intermediate levels of syncopation, or pulse entropy, one may feel a strong need to reinforce the meter by moving in time with the beat.

The *mirpulseclarity* function in the MIRToolbox (Lartillot et al., 2008) uses the EntropyAutocor heuristic to compute the entropy of a music's autocorrelation curve. This method is selected out of many to compute syncopation for several reasons. Firstly, previous studies (Lumaca et al., 2019; Gold et al., 2019; Spiech, Hope, Guilherme, Sioros, Endestad, Laeng, & Danielsen, 2022) have demonstrated the relevance of entropy for human perception of musical complexity and predictability. Additionally, considering rhythmic complexity to emerge from the entire rhythmic structure is advantageous (Spiech, Hope, Guilherme, et al., 2022). Therefore, entropy, derived from the entire autocorrelation curve, is deemed more significant than the maximum correlation value of a single point. Finally, the use of entropy helps position the findings within the broader psychological and scientific literature, where it is utilized to gauge uncertainty (Spiech, Hope, Guilherme, et al., 2022).

3.6 FACTORS INFLUENCING GROOVE

3.6.1 Influence Of Musical Practice

The conclusions about the impact of musical instruction are conflicting. Several studies have examined how musical training influences the perception of rhythmic groove. Matthews et al. (2019) discovered that overall groove evaluations were equal for musicians and non-musicians. In contrast to non-musicians, they discovered that musicians preferred rhythms with medium syncopation over those with high syncopation. Subsequent research supported this finding (Matthews et al., 2022). It's worth noting that these studies only included young people who had substantial exposure to groove-related musical genres. Senn et al. (2018) investigated the effect of expertise (professional musicians, amateur musicians, and non-musicians) on groove ratings with drum patterns as stimuli. They discovered that skilled musicians rated complicated rhythmic patterns better for groove, whereas amateur musicians and non-musicians preferred simpler rhythms. This contradicts Matthews et al.'s (2019) findings, which showed that musicians preferred medium syncopated rhythms to high syncopated rhythms.

Rhythmic abilities were also found to affect the groove sensation. In terms of specific musical capabilities, rhythmic abilities have been demonstrated to influence how people experience groove. Spiech, Sioros, Endestad, et al. (2022) investigated the relationship between groove ratings and rhythmic complexity (i.e., syncopation and pickup) in two groups: high-beat-perceivers and low-beat-perceivers, as defined by Computerised Beat Alignment Test (CA-BAT) scores (Harrison and Müllensiefen, 2018). Their findings revealed that groove ratings and rhythmic complexity had an inverted U-shaped association for high-beat-perceivers, but a negative linear relationship for low-beat-perceivers. However, it was not that people's perceptions of groove changed; rather, participants with higher rhythmic ability had a stronger tendency to rate music "in sync" higher. Overall, these findings indicate that, while the groove experience is similar across individuals (e.g., an inverted U-shaped relationship between the groove experience and the degree of syncopation, as well as a preference for more synchronized rhythms), the general tendency is stronger in experts (including dancers) (Etani et al., 2024).

The ability to recognize groove in music, distinguishing between high and low-groove music, is thought to be linked to musical and dance sophistication. This can be measured using the Goldsmith Music Sophistication Index (Gold-MSI) for musical training and perceptual abilities, and the Goldsmith Dance Sophistication Index (Gold-DSI) for social dancing (O'Connell et al., 2022). Another study discovered that, while dancers and non-dancers had similar ratings of groove and the optimal level of syncopation for the groove experience, dancers had a greater association (Cameron et al., 2023). These findings imply that people with high musical expertise, as well as those with high dancing expertise, who are thought to have stronger rhythmic ability, prefer rhythms with moderate syncopation. Additional factors that could potentially impact the groove experience include the duration and intensity of musical training, as well as the general levels of everyday musical engagement. These factors can be evaluated using the Goldsmiths

Musical Sophistication Index (Gold-MSI) (Müllensiefen et al., 2014) for whether and how they might affect groove. Nonetheless, the differences and similarities between musicians and non-musicians in the groove have not been adequately addressed and warrant more exploration.

3.6.2 Influence Of Reward Sensitivity

When studying the relationship between music, learning, and emotion, it is critical to acknowledge that there is considerable individual variance within the general population. According to responses to the extended Barcelona Music Reward Questionnaire (eBMRQ) (Mas-Herrero et al., 2013; Cardona et al., 2022), musical reward is multidimensional, with six factors: sensorimotor reward (moving to music), social reward (sharing music with others), music-seeking (finding new music), emotion evocation, mood regulation, and absorption into music. Although most people find music rewarding in these ways, those with musical anhedonia describe a loss of sensitivity to the rewards of music listening across these dimensions (Kathios et al., 2024; Loui et al., 2017). Specific musical anhedonia is defined as a selective lack of pleasurable responses to music, despite normal hedonic responses to other sensory and aesthetic stimuli, as well as normal auditory perceptual capacities (Mas-Herrero et al., 2018, 2014; Belfi & Loui, 2020). Those with musical anhedonia may have difficulty with predictive coding, particularly in mapping tonal predictions to reward resulting in lower pleasure from groove (Benson et al., 2024; Romkey et al., 2024). Nonetheless, persons having musical anhedonia may be able to maintain the U-shaped curve for groove by moving ratings (Romkey et al., 2024). The sensation of groove may differ from other types of musical pleasure in that the desire to move may be the primary source of the pleasurable experience.

Additionally, the inclination towards complexity may be associated with eBMRQ. Individuals with a higher sensitivity to reward tend to prefer stimuli with greater perceived complexity. For instance, individuals with very high reward sensitivity (referred to as "musical hyper hedonics" by Mas-Herrero et al., 2014) showed a preference for the most complex stimuli, leading to a consistent increase in pleasure as complexity increased, instead of following an inverted-U curve (Benson et al., 2024). Thus, it might be important to account for the differences in pleasure derived from music engagement by the listeners.

4. RESEARCH HYPOTHESIS

To explore the relationship between rhythmic complexity and perceptual rhythmic skills, this pilot study aims to gather subjective groove ratings using complex and naturalistic musical stimuli from the Computerized Adaptive Beat Alignment Test (CA-BAT). Specifically, the study examines how pulse entropy, the predictor of rhythmic complexity, relates to participants' ratings of pleasure and their wanting to move in response to the stimuli.

Additionally, this investigation will consider individual differences, incorporating the level of reward sensitivity and musical training.

Drawing from previous literature (Witek et al., 2014), the hypothesis posits that pulse entropy is anticipated to demonstrate an inverted U-shaped relationship with ratings of pleasure and the wanting to move.

5. METHODS

5.1 PARTICIPANTS

120 university students between the ages of 18 to 35 (M= 23.65, SD=3.88) took part in the study (36-male, 83-female, 1-other). All participants were neurologically healthy and did not report any hearing impairments. Participants were non-musicians, defined as having received less than two years of formal or informal musical training: to check this information, we administered the Musical Training subscale of the Gold-MSI questionnaire (Müllensiefen et al., 2014). They were either English (N = 35) or Italian (N = 85) and completed the experiment in their corresponding language.

5.2 STIMULI

The stimuli utilized are taken from the Computerized Adapted Beat Alignment Test (CA-BAT), a variant of the Beat Alignment Test (BAT). The Beat Alignment Test (BAT) is a comprehensive test battery designed to assess musical beat-processing abilities within the general population. This assessment evaluates individuals' capacity to synchronize with a beat in music, as well as their ability to perceive a beat independently of synchronization (Iverson & Patel, 2008). The BAT requires listeners to attempt to detect misalignment between a metronome and a musical excerpt. This test investigates the listener's perceptual abilities using the beat alignment paradigm developed by Iversen and Patel (2008). In this test, participants wear headphones and have to listen to 32 musical compositions that run around 12 seconds each, with a succession of timed beats at the same distance as a metronome, and then reply if the beat was synchronous or asynchronous using the keyboard. Kinned to that, the purpose of the CA-BAT is to appraise the listener's aptitude for beat perception through the utilization of an adaptive iteration of the Beat Alignment Test (BAT). This adaptive test customizes the difficulty level to suit each participant by adjusting to their prior responses (Harrison & Müllensiefen, 2018). Thus, we used a total number 25 stimuli, taken from the CA-BAT. Each track is overlaid with a metronome track composed of a 20 ms sine tone with frequency 1000 Hz and a 10 ms fade-out. For the employment in our experiment, each track was cut at 5000 ms duration. For this experiment, we eliminated the metronome and presented only the pure musical tracks with varying rhythmic complexity. We calculated the pulse entropy measure for each track. The CA-BAT stimuli were employed to assess entropy in the pure tracks, irrespective of the presence of the metronome because the aim is to utilize the tracks with the metronome when examining the relationship between pulse entropy and rhythmic abilities using this stimuli (See, *7.3 Future Directions*). The *mirpluseclarity*, present in MIRtoolbox (Lartillot et al., 2008) of MATLAB, was used for objective rhythmic complexity measure. The "EntropyAutocor" heuristic was used to compute the entropy of the music's autocorrelation curve. This is used to estimate the rhythmic clarity, indicating the strength of the beats estimated by the mirtempo function. The estimates of pulse entropy in the MIRToolbox generally aligned with the perceived rhythmic complexity of the stimuli, as informed by musicological literature on groove (Câmara & Danielsen, 2018; Danielsen et al., 2019). The pulse entropy determined the rhythmic complexity of the BAT stimulus ranged from lowest to highest value (min = .686, max = .815, mean = .753) meaning from lowest to highest unpredictability (See, *10. Appendices*) .

5.3 MATERIAL

5.3.1 Extended Barcelona Music Reward Questionnaire (eBMRQ)

The eBMRQ is an extended version of the original BMRQ (Mas-Herrero et al., 2013). In its original version, the questionnaire comprised a brief self report survey designed to evaluate different aspects of music and reward experiences. Participants provide ratings for various statements related to their emotional engagement with music. Cardona et al. (2022) introduced and validated an expanded version of BMRQ (eBMRQ) with six primary factors. As such, the eBMRQ seeks to be a comprehensive and accurate tool for examining the various characterizations of individual sensitivity to pleasure in music. In this last version, the questionnaire comprises 24 questions (5 items each except the absorption in music having 4 items), categorized into 6 sub-factors: music-seeking, emotion evocation, mood regulation, sensorimotor engagement, social reward, and absorption in music. Participants are asked to rate their level of agreement with each statement on a five-point scale, from fully disagree (1) to fully agree (5). An overall score can be derived by summing up the individual sub-factor scores. Higher scores indicate higher musical reward sensitivity. The ORION reliability (Ferrando & Lorenzo-Seva, 2018) of the six subscales ranged from 0.836 to 0.932, while the ORION reliability of the overall dimension was 0.952. For this study, we used the English and the translated Italian version of the eBMRQ (Carraturo et al., 2023). The Italian version of the eBMRQ, similar to the original English version, exhibits satisfactory psychometric properties and construct validity (Carraturo et al., 2023). This suggests that the Italian adaptation of the eBMRQ is a dependable instrument for gauging sensitivity to music reward. The following variables are recorded:

1. ***Musical Seeking***: This score reflects the level of active engagement with music, including the time, effort, and resources you invest in listening to and learning about music. For example, "I inform myself about music I like."

2. ***Emotion Evocation***: This score indicates the extent to which music evokes strong emotions. Seeking out emotionally impactful music, experiencing tears or strong emotions while listening, or feeling chills all contribute to a higher score. For example, "I get emotional listening to certain pieces of music."

3. ***Mood Regulation***: This score represents how effectively music helps to calm, comfort, and improve mood. For example, "Music calms and relaxes me."

4. ***Sensorimotor***: This score measures the physical experience while listening to music. A higher score is indicative of physical responses such as dancing, tapping, or singing along to the music. For example, "I can't help humming or singing along to music that I like."

5. ***Social Reward***: This score measures the extent to which music fosters a sense of connection with others. Feeling a stronger social bond when listening to music together, singing or playing music with others, or attending concerts as a group contribute to a higher social reward score. For example, "When I share music with someone I feel a special connection with that person."

6. ***Absorption in Music:*** This score measures the extent of absorption in music that can be described as a willingness to be fully immersed in sensory stimuli, experiencing deep involvement without distraction. For example, “I sometimes feel like I am “one” with the music.”

Calculation: The subscores are calculated by taking the sum of the scores for questions in each sub-factor, taking into account reverse-coding of some questions (#2 and #5). Total score is calculated by taking the sum of all 6 subscores.

5.3.2 Goldsmiths Musical Sophistication Index (Gold-MSI)

The Gold-MSI is a self-report inventory designed to measure individual differences in musical sophistication (Müllensiefen et al., 2014). It assesses the ability to engage with music in a flexible, effective, and comprehensive way. The items are grouped into five subscales: active engagement (nine items), perceptual abilities (nine items), musical training (seven items), singing abilities (seven items) and emotions (six items). Participants are asked to indicate how much they agree with items 1-31 using a Likert scale from 1 (“Completely Disagree”) to 7 (“Completely Agree”). The response options are labeled differently for each of the remaining items (items 32-38) investigating the subjects’ amount of engagement in several domains of musical experience (for example: listening to music, participating at music events), on a 7-point Likert scale, from a minimum amount to a given maximum amount. A higher total score on the Gold-MSI indicates higher levels of musical sophistication. The instrument has been validated, and factor analyses showed that the construct of musical sophistication is best described by a bifactor model, with a general factor, General Musical Sophistication, and five subfactors

(Müllensiefen et al., 2013). The questionnaire was translated into Italian, and the translated items were used by Italian participants. The inventory includes sub-scales to measure the following facets of musical sophistication:

1. ***Active Engagement***: This factor covers a range of active musical engagement behaviors, such as keeping track of new music, searching the internet for music-related content, and allocating time and money to musical activities. For example, "I often read or search the internet for things related to music."

2. ***Perceptual Abilities***: This factor represents self-assessment of various musical abilities, particularly related to music listening skills, including the ability to compare and discuss differences between musical performances and recognizing when someone sings or plays out of tune. For example, "I can't tell when people sing or play out of tune."

3. ***Musical Training***: This factor combines questions about the extent of musical training and practice, as well as self-assessed musicianship. For example, e.g. "I engaged in regular daily practice of a musical instrument including voice for __ years" , "I would not consider myself a musician", "I have never been complimented for my talents as a musical performer" etc.

4. ***Singing Abilities***: This factor reflects different skills and activities related to singing, including the ability to learn new songs and sing in harmony. For example, "After hearing a new song two or three times I can usually sing it by myself."

5. ***Emotions***: This factor covers active behaviors related to emotional responses to music, such as being able to talk about the emotions evoked by a piece of music and choosing music that can trigger strong emotional responses. For example, "I am able to talk about the emotions that a piece of music evokes in me."

6. ***General Musical Sophistication***: This factor incorporates aspects from all the above-mentioned subscales.

Calculation: For this experiment, we only used the Musical Training subscale to check for musical expertise of the participants. The musical expertise subscale has 7 items on a 7 point likert scale, with reverse coding of some questions (#3 and #7). The total score is calculated by taking the sum of all items with the maximum score being 49.

5.4 PROCEDURE

The participants were recruited to perform the experiment through word of mouth or email notification to university students. They were exclusively asked to carry out the experiment from the laptop (no smartphone or tablets), as well as to wear earphones/earpods/headphones while doing it. They were requested to follow the instructions that will appear on the screen in order to get the experiment done.

First, participants completed some demographic questions (age, gender and years of music training). All information is mandatory to proceed with the experiment.

This was followed by the presentation of the 25 short musical experts (see above). After each stimulus was presented, participants were required to rate pleasure and wanting to move (two subcomponents of groove). Pleasure is assessed by the question 'How much pleasure do you experience listening to this musical pattern?', while wanting to move with ‘How much does this musical pattern make you want to move?’. Participants used their mouse to select their rating on the five-point scales from 1 to 5 where 1 indicated ‘not at all’ and 5 indicated ‘a lot’.The presentation of the stimuli was counterbalanced, while the order of the rating scales was not, as the primary focus of the study was on the Pleasure ratings of the tracks. Participants were not able to proceed to the next stimulus until each stimulus had been presented in its entirety and a rating had been selected on both scales. Following the completion of all tracks, the participants filled in the eBMRQ and Musical training subscale of the Gold-MSI (Müllensiefen et al., 2014). The participants took the online test using the software Psychopy (Peirce, 2007, 2009; Peirce et al., 2019), which was implemented on the online platform Pavlovia (https://pavlovia.org/), used for presenting stimuli and collecting data. The entire experiment lasted approximately 30 minutes, including instructions, listening and rating of musical excerpts, and questionnaires.

5.5 DATA ANALYSIS

The data from all the participants who completed the experiment were stored in Pavlovia. Before analyzing data, we checked if some participants always voted the same value of Pleasure and Wanting to move and if some participants repeated more than 5 times the same response. No participants always voted the same response, and just one participant repeated the vote “1” 6 times. Thus, considering a single case happened only in this specific participant, we decide to retain the complete sample for further analysis.

We performed a linear mixed model using pulse entropy values as predictor and Pleasure rating as dependent variable; then we performed the same model using Wanting to move as dependent variable. Additionally, we add the eBMRQ scoring as a predictor, to investigate the effect of musical reward sensitivity on groove ratings. To understand deeply which subcomponent of musical reward plays a major role in driving our groove ratings, we performed one linear mixed model for each subscales of the eBMRQ (see above). Additionally, we predicted the pleasure and wanting to move rating based on the musical training subscale of the Gold-MSI. In all the models we inserted the polynome of pulse entropy to account for the quadratic slope (u-shape), which is the focus of our analyses. Random intercepts for participants are included in all models. All the analyses were carried out with linear mixed models (LMM) using *lme4* package (Bates et al., 2015) in R statistical language (R Core Team, 2023). R2 for multilevel models was estimated using package *performance* (Lüdecke et al., 2021; Nakagawa & Schielzeth, 2013). We reported marginal and conditional R2 to consider first the variance of fixed effects only and then the total model's variance (fixed and random effects).

6. RESULTS

6.1 Main effects of Pleasure and Wanting to Move

The analysis for main effects demonstrates a regression model with quadratic slope for pulse entropy (marginal R2 = 0.008, conditional R2 = 0.164) significantly predicted pleasure (t (2878) = -3.16, p = .002), depicting an inverted u-shape, as expected (see Figure 3 A).

Similarly, a regression model with quadratic slope for pulse entropy (marginal R2 = 0.037, conditional R2 = 0.206) significantly predicted wanting to move (t (2878) = -6.02, p = < .001), depicting an inverted u-shape (see Figure 3 B).

A **B**

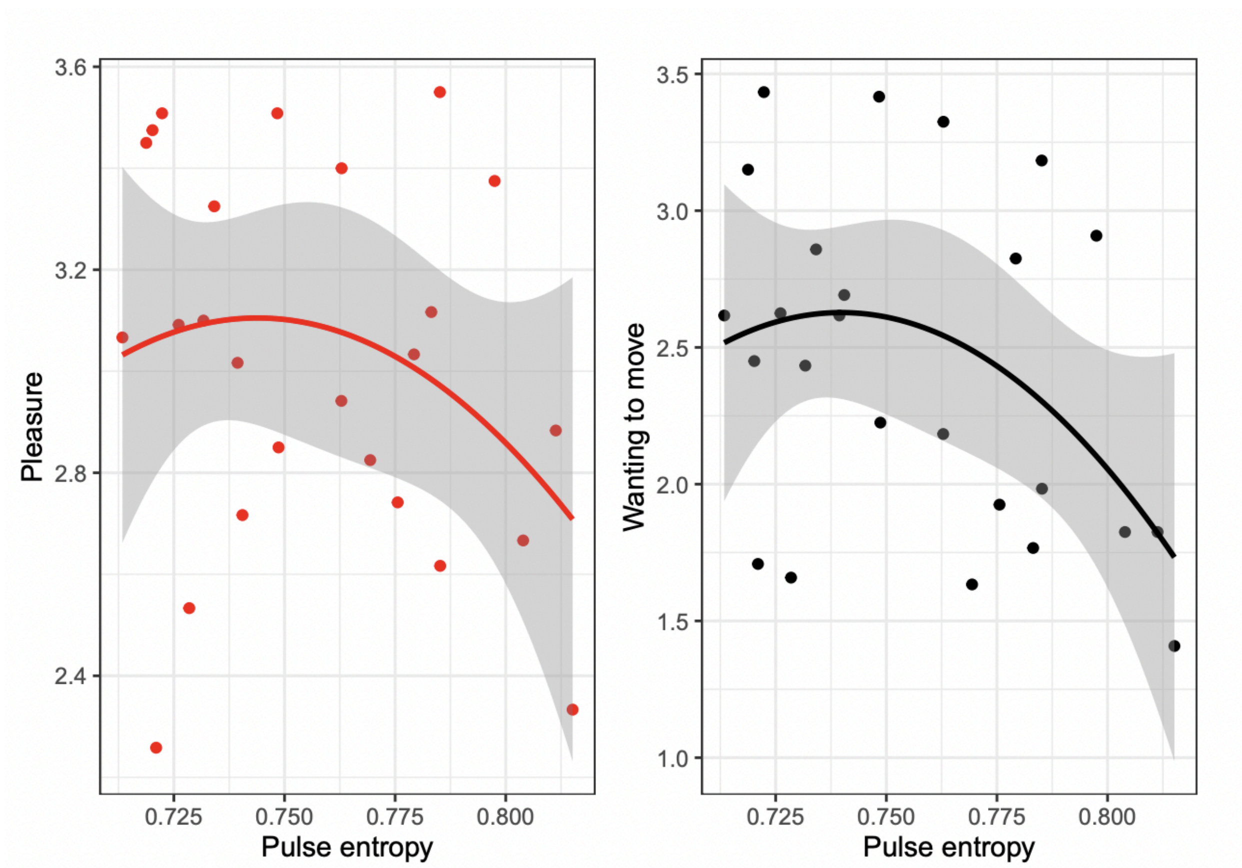


Fig 3: Scatter plots with a quadratic fitted curve and shaded confidence intervals. (A) relationship between pulse entropy and Pleasure. (B) relationship between pulse entropy and Wanting to move. The colored dots represent the musical tracks, the colored lines represent the fitted curves, and the shaded gray areas represent the confidence intervals.

6.2 Effect of pleasure and Wanting to move in interaction with eBMRQ

*6.2.1 Pleasure * eBMRQ*

When adding to predictors the eBMRQ scoring, we failed to find a significant main quadratic effect of the pulse entropy (t(2876) = 1.203, p = .229) and a significant main effect of eBMRQ (b = .01, t(118) = 1.582, p = .116). Otherwise, the interaction between the quadratic effect of pulse entropy and the eBMRQ indicate a trend towards significance (t(2876) = -1.714, p = .087), reflecting a nuanced stronger inverted u-shape with higher eBMRQ values, as reported in Figure 4.1 (marginal R2 = 0.013, conditional R2 = 0.166). For clarity of interpretation, we show one line (blue) for the mean scoring, one for 1 sd higher than mean (green) and one for 1 sd lower than the mean (red).

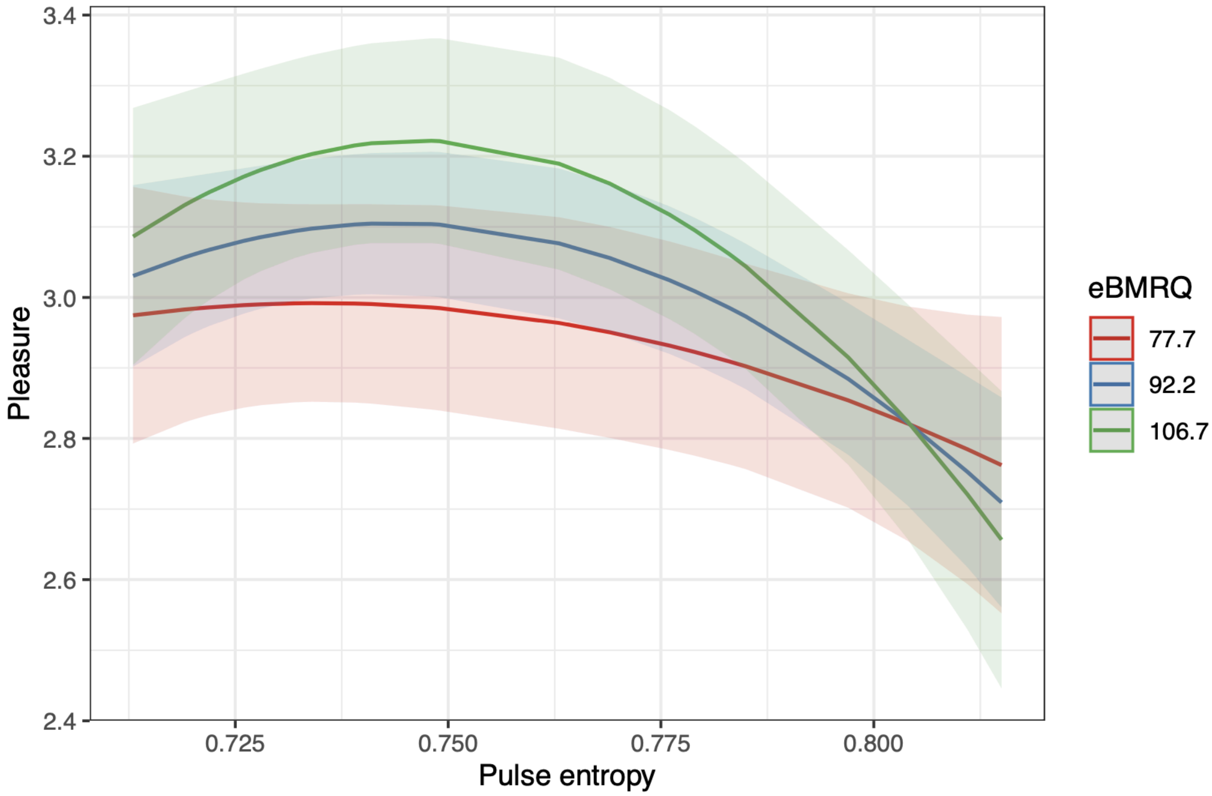


Fig 4.1 The relationship between Pulse Entropy and Pleasure ratings changes at different levels of eBMRQ. The coloured lines represent the predicted values of Pleasure at different levels of eBMRQ scoring. The inverted U-shape is more pronounced for higher eBMRQ values, indicating a stronger optimal level of Pulse Entropy for achieving higher Pleasure.

*6.2.2 Wanting to Move * eBMRQ*

The linear mixed model indicates that, while the quadratic effect of pulse entropy on Wanting to move is not significant (t(2876) = -0.262, p = .794), eBMRQ has a significant main effect (b = .01, t(118) = 1.984, p = .050, marginal R2 = 0.043, conditional R2 = 0.207). Interaction terms between pulse entropy and eBMRQ are not significant (t(2876) = -0.682, p = .495), suggesting no meaningful interaction between these variables in predicting Wanting to move. Thus, higher eBMRQ scores are associated with a slight increase in the desire to move, independent of pulse entropy levels as shown in Figure 4.2.

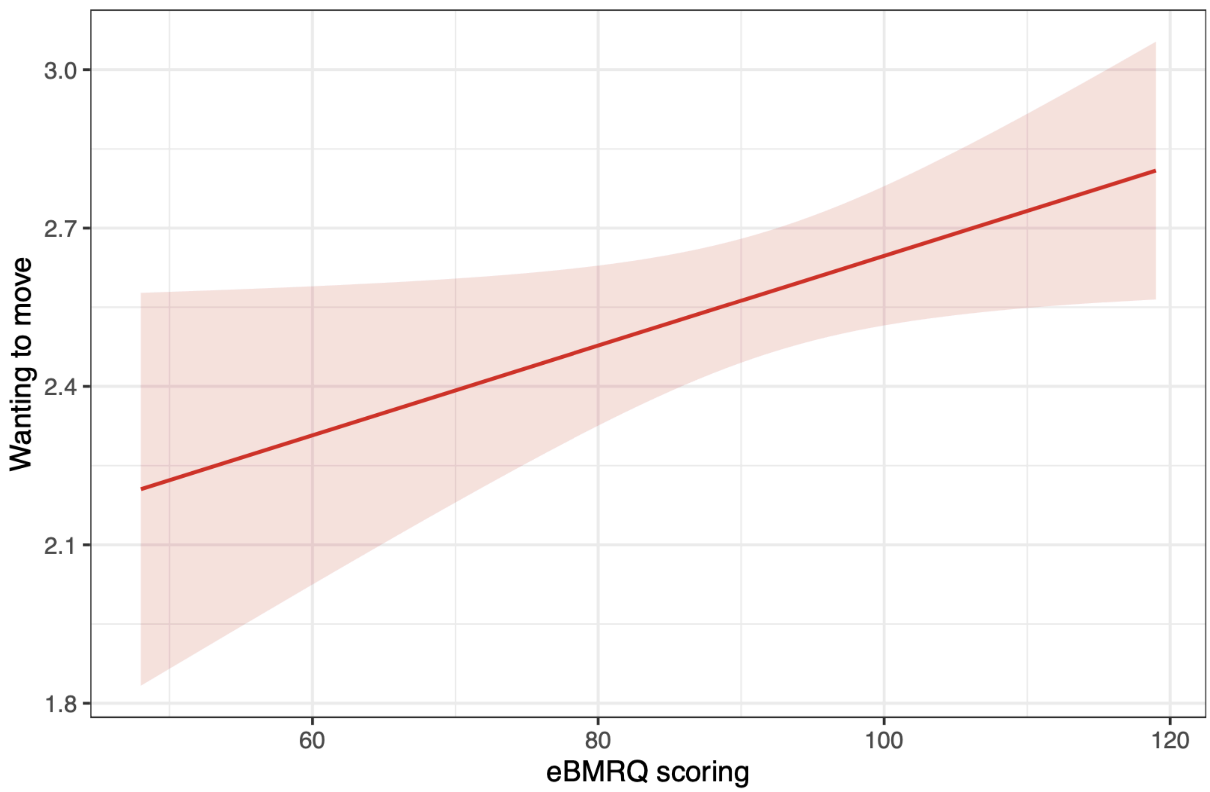


Fig 4.2 Linear relationship between eBMRQ scores and Wanting to Move. Higher eBMRQ scores are positively associated with an increased desire to move, independent of pulse entropy levels.

6.3 Investigating the eBMRQ subscales

6.3.1 Pleasure

When predicting the Pleasure by entropy and by each subscale of the eBMRQ, we found the subsequent effects: 1) the Social subscale shows a main significant effect on pleasure (b = .04, t(118) = 2.76, p = .006), meaning an higher pleasure rating with higher scoring of Social. 2) Crucially, SensoryMotor subscale significantly predict the pleasure rating in interaction with the pulse entropy (t(2876) = -1.97, p = .049), meaning the eBMRQ significant effect in modulating the effect of pulse entropy is driven by the sensory motor subscale. 3) None of the other subscales show a main significant effect on pleasure ratings (all ps > .175), or interaction with the pulse entropy (all ps > .092).

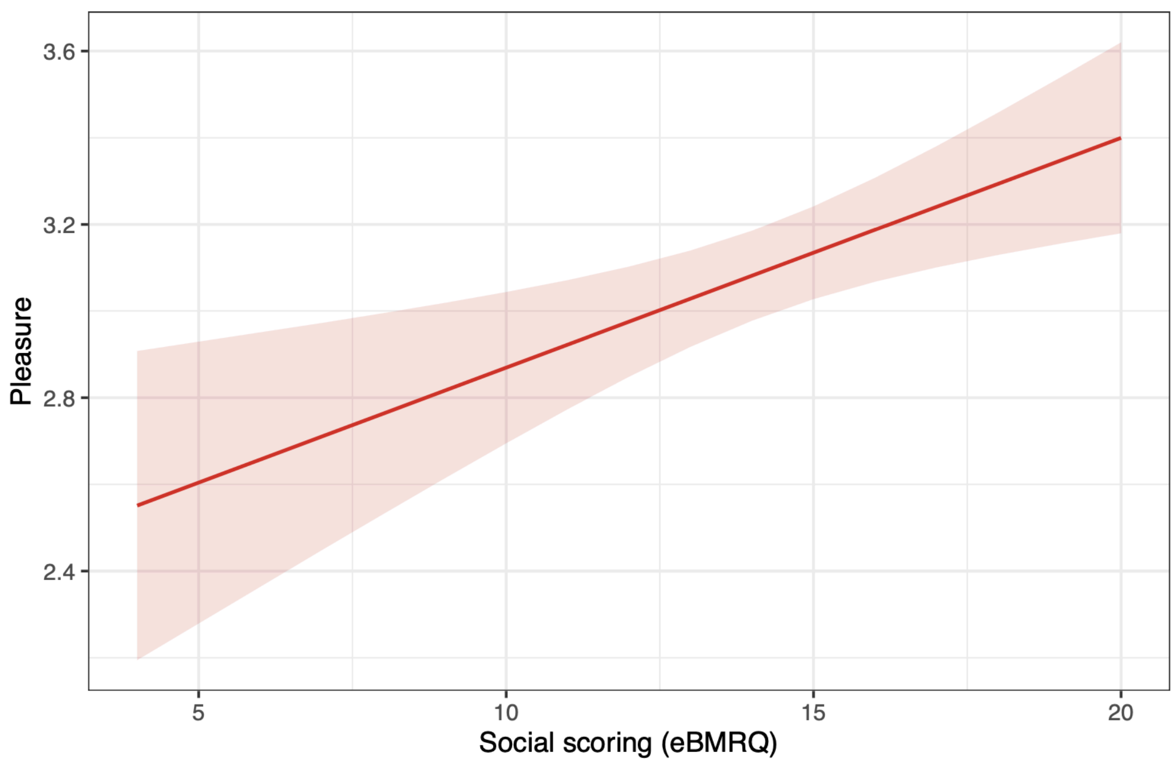


Fig 5.1.1 Linear relationship between Social scoring and Pleasure. Higher social scores are positively associated with higher pleasure ratings, independent of pulse entropy levels.

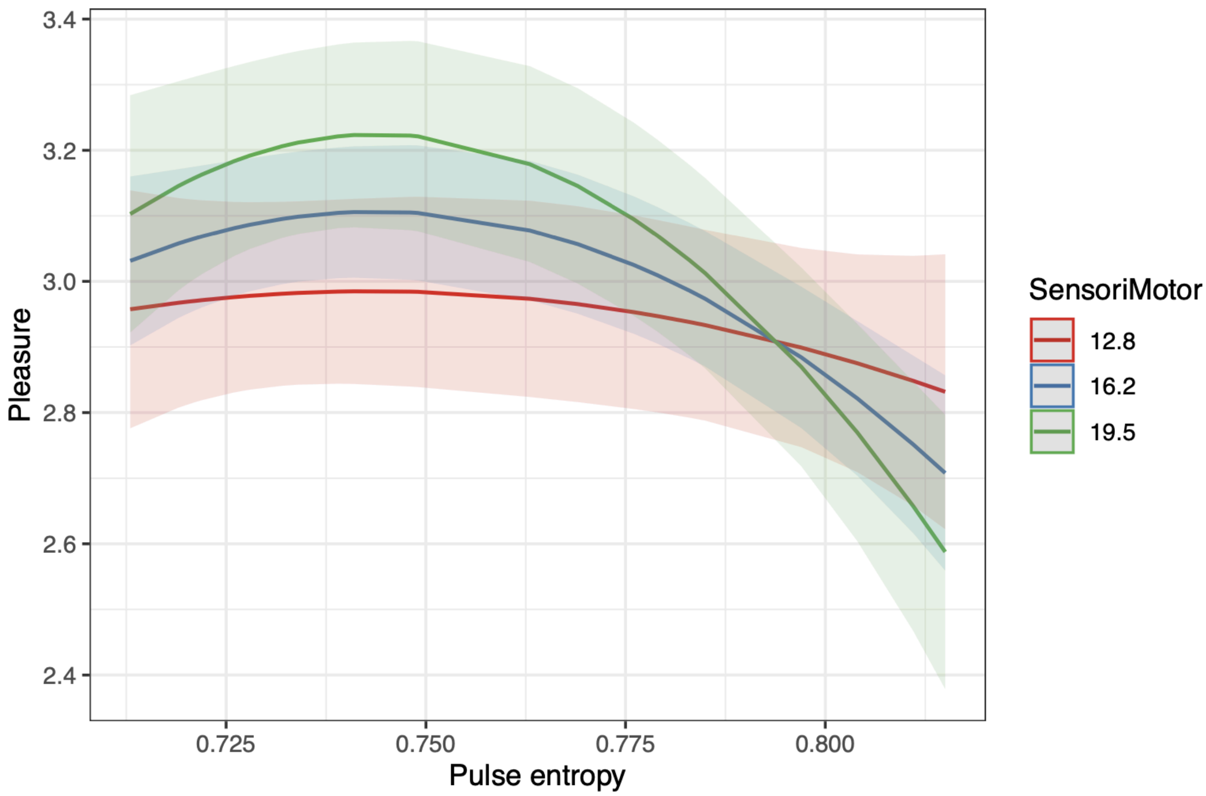
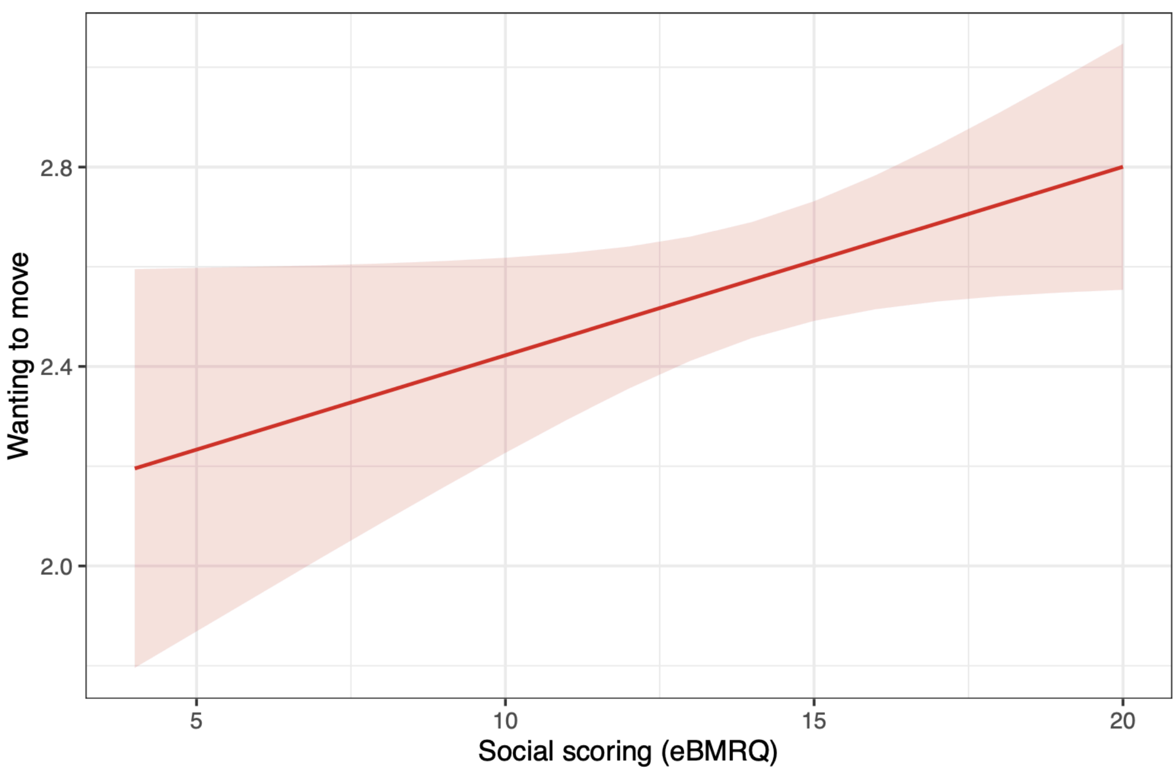


Fig 5.1.2 Relationship between Pulse Entropy and Pleasure ratings. Colored Lines represent different levels of the SensoriMotor subscale (mean = blue; mean + 1 SD = green; mean - 1 SD = red). Higher SensoriMotor scores amplify the pleasure response to changes in Pulse entropy, showing a more pronounced peak in Pleasure at moderate Pulse entropy levels before declining.

6.3.2 Wanting to Move

When predicting the WM by entropy and by each subscale of the eBMRQ, we found a marginally significant main effect of Social (b = 0.03404, t(118) = 1.973, p = 0.051) (see Figure 5.2.1 A) and a significant main effect of SensoriMotor (b = 0.03345, t(118) = 2.129, p = 0.035) (see Figure 5.2.1 B). The only marginally significant effect of the interaction is SensoryMotor x pulse entropy (t(2876) = -1.704, p = 0.088) (see Figure 5.2.2). All the other models showed no significant effect of the subscale on Wanting to move ratings (all ps > .171), nor interactions with the pulse entropy (all ps > .314).

A



B

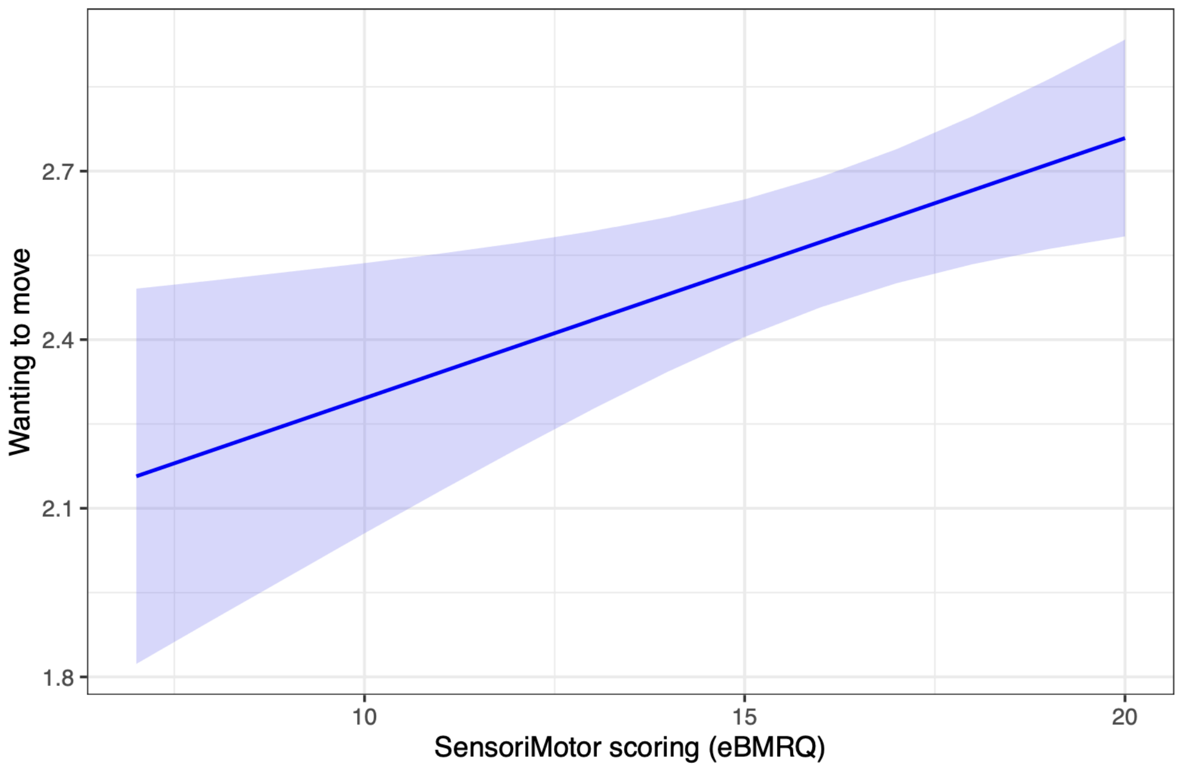


Fig 5.2.1 Linear regression between (A) Social scoring and (B) SensoriMotor scoring with Wanting to move ratings, respectively. Both Social scoring and SensoriMotor subscale scores positively influence the Wanting to move ratings.

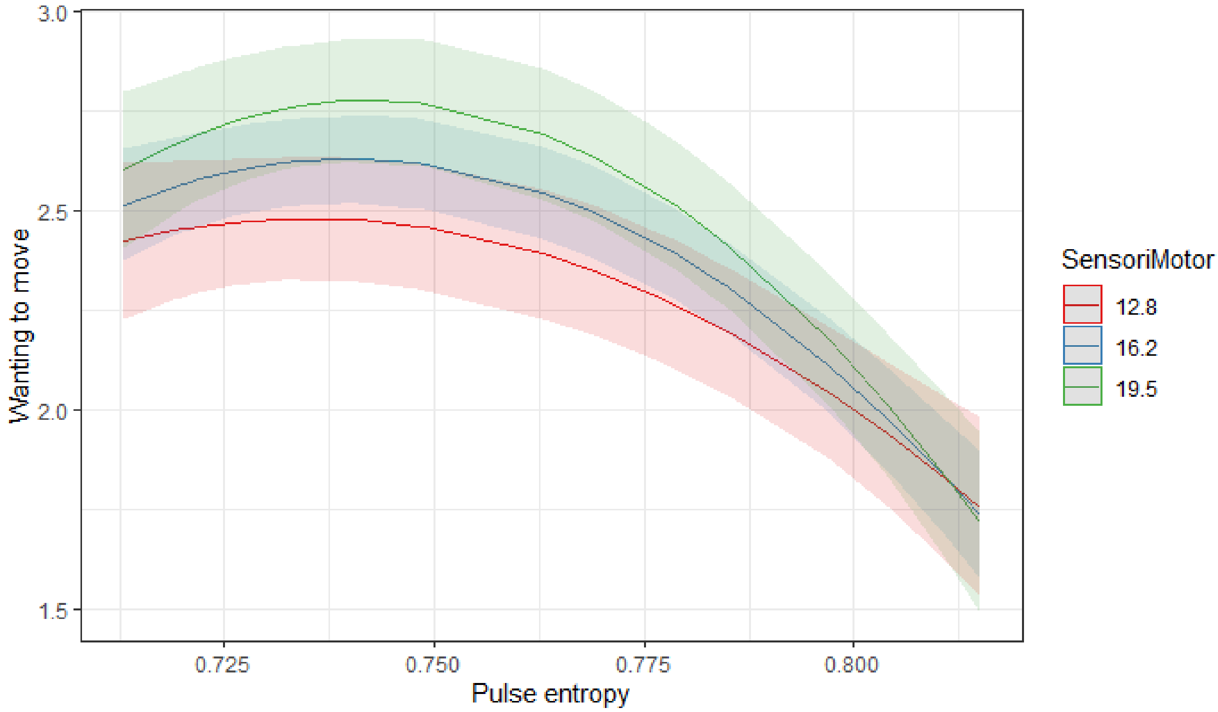


Fig 5.2.2 Relationship between Pulse Entropy and Wanting to move ratings. Colored Lines represent different levels of the SensoriMotor subscale (mean = blue; mean + 1 SD = green; mean - 1 SD = red). Higher SensoriMotor scores amplify the wanting to move response to changes in Pulse entropy, showing a more pronounced peak in desire to move at moderate Pulse entropy levels before declining.

6.4 Effect of pleasure and Wanting to move in interaction with Musical Training

When predicting Pleasure and Wanting to move ratings by the interaction of pulse entropy and musical training, we did not find a significant main effect of musical training subscale of the Gold-MSI (M= 17.62, SD=9.09) on either Pleasure (b = 0.0053, t(118) = 0.043, p = 0.966) or

Wanting to move (b = 0.0046, t(118) = 0.035, p = 0.972). Similarly, there were no significant interactions (t(2876) = -0.063, p = 0.950 for pleasure; t(2876) = -0.222, p = 0.824 for wanting to move), meaning similar ratings of Pleasure and Wanting to move at different levels of musical training (marginal R2 (pleasure) = 0.010, conditional R2 (pleasure) = 0.165; marginal R2 (wanting to move) = 0.037, conditional R2 (wanting to move) = 0.207).

7. DISCUSSION

The study aimed to investigate how the complexity of rhythm in musical stimuli affects groove behavior in the Computerised Beat Alignment Test (CA-BAT). The hypothesis was that pleasure and wanting to move ratings would show an inverted U-shaped curve for different levels of pulse entropy in the CA-BAT tracks. The study included 120 participants who rated 25 musical tracks from the CA-BAT in terms of pleasure and wanting to move on a five-point scale. Data from the eBMRQ and Musical training subscales of the Gold-MSI were also gathered.

A linear mixed model analysis, using pulse entropy values as the independent variable and groove ratings (particularly, pleasure and wanting to move) as the dependent variables, revealed a quadratic relationship between both pulse entropy and pleasure and pulse entropy and wanting to move. Both relationships exhibited an inverted U-shaped curve, showing that there is an optimal degree of pulse entropy for maximizing these feelings. Feelings decrease below or above this ideal threshold. The sentiments of pleasure and wanting to move are decreased at low and high levels of pulse entropy, respectively, although they peak at moderate levels. These findings suggest that a particular level of rhythmic variability (pulse entropy) is optimal for increasing pleasure and motivation to move. Too little or too much variability may not be as enjoyable or motivating.

These findings are consistent with our hypothesis and validate the CA-BAT stimuli that follow an inverted U shape for groove. According to predictive coding, medium-complexity rhythms may increase pleasure and motivation to move by striking a balance between predictability and uncertainty (Salimpoor et al., 2015). This corresponds to the concept of an inverted U-shape and is compatible with previous notions that optimal levels of arousal or complexity are the most engaging or enjoyable (Witek et al., 2014; Matthews et al., 2022; Vuust & Witek, 2014).

7.1 EFFECT OF MUSICAL REWARD

We investigated the impact of an additional variable, eBMRQ score, on the previous regression model to comprehend how it influences pulse entropy in predicting the outcomes of pleasure and wanting to move. When eBMRQ was added to the model as an additional predictor, the previously observed significant quadratic effect of pulse entropy disappeared. This suggests that after accounting for eBMRQ, pulse entropy alone is no longer a significant predictor of pleasure or wanting to move. The effect for each component is as follows:

7.1.1 Pleasure and Musical Reward

The main effect of the eBMRQ was not statistically significant, implying that the eBMRQ score alone did not predict pleasure. However, a reported interaction effect between the quadratic term of pulse entropy and eBMRQ indicates a potential trend toward significance. This suggests an interesting interaction effect to investigate, implying that the link between pulse entropy and pleasure may differ based on the eBMRQ score.

The trend towards a significant interaction indicates that the eBMRQ score moderates the influence of pulse entropy on pleasure. When eBMRQ scores are higher, the relationship between pulse entropy and pleasure may exhibit a more prominent inverted U-shape. This suggests that persons with higher eBMRQ scores have a more evident peak in the pleasure variable at moderate levels of pulse entropy, whereas lower and higher levels of pulse entropy significantly reduce pleasure.

The inclusion of eBMRQ in the model complicates the relationship between pulse entropy and pleasure. While neither pulse entropy nor eBMRQ alone significantly predicts pleasure, there is a suggestive interaction indicating that the effect of pulse entropy is stronger among persons with higher eBMRQ scores, which warrants additional exploration. This interaction, albeit not statistically significant, suggests that persons with greater eBMRQ may feel more obvious peaks in pleasure at intermediate pulse entropy levels. The above findings may provide a counterpoint to those of Benson et al (2024), who suggest that for highly reward-sensitive individuals, pleasure increases steadily with complexity, rather than following the more typical inverted-U-shaped pattern in which pleasure peaks at a moderate level of complexity before decreasing.

7.1.2 Wanting to Move and Musical Reward

The linear mixed model explores the relationship between pulse entropy, eBMRQ scores, and the Wanting to Move variable. As previously stated, the study determined that the quadratic effect of pulse entropy on Wanting to Move is not statistically significant. This finding demonstrates that changes in pulse entropy (high, low, or intermediate) have no significant effect on people's urge to move. In contrast, eBMRQ scores have a significant overall effect on the desire to move, suggesting a positive link.

Furthermore, the interaction between pulse entropy and eBMRQ scores is not significant. This suggests that the effect of eBMRQ scores on the desire to move is independent of pulse entropy levels. To put it another way, the relationship between eBMRQ scores and Wanting to Move remains consistent despite variations in pulse entropy. The main conclusion is that, while pulse entropy does not significantly predict the desire to move, eBMRQ scores do have a significant, albeit minor, positive effect. The lack of a significant interaction effect implies that the relationship remains consistent regardless of pulse entropy levels.

In conclusion, while pulse entropy does not directly or quadratically affect the wanting to move, eBMRQ scores may reflect aspects of personal motivation or readiness that do have a small but significant positive impact on movement. This effect remains stable and consistent across different levels of pulse entropy, implying that higher eBMRQ scores are generally related to a stronger desire to move, irrespective of any changes in pulse entropy. These findings may be indicative of the underlying intersection of reward processing and the motor processes in groove sensation. It adheres to the idea that medium-complexity rhythms stimulate these networks (motor and reward) by balancing regularity for beat generation with syncopations that challenge expectations, resulting in pleasure and movement (Matthews et al., 2020).

These outcomes, along with the above results, justified further exploration of the eBMRQ subscales measuring rhythmic complexity and groove behavior. Although rhythmic complexity is the primary driver of groove behavior (Matthews et al., 2019), the previously mentioned findings highlight the significance of reward sensitivity when investigating groove.

7.1.3 Investigating the eBMRQ subscales

The results analyze how pulse entropy and different subscales of the eBMRQ predict pleasure and wanting to move. The two main significant dimensions were the Social and and the SensoryMotor subscales. The remaining subscales of the eBMRQ do not show significant main effects on Pleasure or Wanting to move, nor do they interact significantly with pulse entropy.

Social Subscale

The analysis revealed that the Social subscale of the eBMRQ has a notably positive impact on pleasure ratings. This suggests that individuals with higher scores on the Social subscale, i.e. those who enjoy or value social interactions with others, tend to experience heightened levels of pleasure. However, in terms of the desire to move, the Social subscale has only a marginally significant effect. This indicates that while higher scores on the Social subscale are somewhat linked to a greater desire to move, the influence is weak and not strongly predictive. In summary, social factors appear to significantly enhance pleasure but have only a modest effect on the desire to move.These findings may highlight the fundamental connections between production, perception, prediction, and social reward that come from rhythm repetition and synchronization. This is indicative of the idea that the dopaminergic reward system plays a causal role in the link between music and social bonding via the prediction mechanism (Savage et al., 2020).

SensoryMotor Subscale

The SensoryMotor subscale plays a crucial role in shaping the relationship between pulse entropy and pleasure. Specifically, as SensoryMotor scores change, the effect of pulse entropy on pleasure also changes, possibly strengthening the inverted U-shaped relationship observed previously. This finding means that the SensoryMotor subscale plays an influential role in modulating the effect of pulse entropy on pleasure. Individuals with higher SensoryMotor scores may experience different levels of pleasure depending on their pulse entropy, perhaps with moderate levels of entropy maximizing their pleasure. This subscale measures sensory and motor engagement, which may be more susceptible to rhythmic variability in pulse. Previous research on how music surprise and entropy interact with pleasure ratings discovered that music with intermediate degrees of complexity (surprise) and uncertainty (entropy) achieved higher pleasure ratings (Cheung et al., 2019; Gold et al., 2019).

In terms of wanting to move, the SensoryMotor subscale shows a significant positive effect. This result indicates that higher scores on the SensoryMotor subscale significantly predict a higher desire to move. Individuals who score higher on the SensoryMotor subscale, which may relate to physical engagement or sensory responsiveness, tend to experience a greater desire to move. Additionally, there is a marginally significant interaction between the SensoryMotor subscale and pulse entropy. Specifically, the interaction might mean that for individuals with higher SensoryMotor scores, the effect of pulse entropy on wanting to move may vary, possibly showing an inverted-U shape or some other modulation. This interaction implies that the impact of rhythmic variability on movement desire is influenced by sensory and motor engagement.The relationship between sensorimotor eBMRQ and wanting-to-move ratings is expected: people who maintain that music makes them want to move are more likely to provide higher wanting-to-move ratings. This is consistent with a prior study on musical reward and groove, which found that the SensoryMotor subscale is uniquely correlated with move assessments among other subscales of the eBMRQ (Benson et al., 2024). Furthermore, previous fMRI studies have demonstrated that the motor system is involved in rhythmic information processing (Gordon et al., 2018), and several studies have found correlations between cortical and subcortical motor areas and beat-related pleasure (Kornysheva et al., 2010; Matthews et al., 2020; Trost et al., 2014).

7.2 EFFECT OF MUSICAL TRAINING

The results also examine whether musical training (as measured by the musical training subscale of the Gold-MSI) and pulse entropy have any effect on ratings of Pleasure and Wanting to move. The musical training subscale of the Gold-MSI did not have a significant effect on either Pleasure or Wanting to move. Additionally, the interaction between pulse entropy and musical training was not significant for either Pleasure or Wanting to move. The lack of significant main effects suggests that musical training, as measured by the Gold-MSI subscale, does not directly impact how much pleasure people experience or their desire to move. The lack of significant interactions implies that the relationship between pulse entropy and pleasure or wanting to move is independent of musical training level. This suggests that the effect of rhythmic variability (pulse entropy) on these experiences is consistent regardless of musical training background.

This implies that both pleasure and wanting to move are influenced more by other factors not captured by the Gold-MSI subscale of musical training or pulse entropy, suggesting a complex interplay of various elements in shaping musical experience. It is important to note here that professional musicians were purposefully excluded from this study. Consequently, the basic level of musical training among non-musicians likely did not exert a significant influence on the observed relationship between rhythmic complexity and perceived groove. However, the inclusion of professional musicians may have yielded different outcomes, potentially revealing a more nuanced interaction between musical expertise and the complexity-groove relationship. As in previous research, which found that musicians consciously employ syncopation to express groove (Madison & Sioros, 2014), and that musical expertise is positively related to the influence of syncopation on groove evaluations (Senn et al., 2018). Matthews et al. (2019) found that musicians are more sensitive to rhythmic and harmonic alterations. This could imply that for those with musical training, non-rhythmic elements have a greater impact on groove experience (Matthews et al., 2020). Some studies reported no influence on musicianship (Witek et al., 2014) or lowered groove assessments in musicians (Hurley et al., 2014). Furthermore, groove studies on musical training should be approached with caution because these studies defined musicianship less narrowly, potentially weakening the impact of training-based internal models or expectancies on the experience of groove.

7.3 LIMITATIONS AND FUTURE DIRECTIONS

This study has several limitations that may affect the findings. The musical excerpts were very short (5 seconds), therefore participants may not be able to engage with the music completely.

Furthermore, the stimuli were instrumental and lacked lyrics, which limited the study's ecological validity, as vocals are common in real-world music. The narrow range of pulse entropy (0.686 to 0.815) may further restrict the capacity to investigate the whole influence of rhythmic complexity. Finally, while the stimuli were counterbalanced, the rating scales were not, potentially leading to bias in favor of pleasure ratings. Future studies could benefit from counterbalancing the rating scales and using longer, continuous tracks rather than brief extracts which would improve the reliability and ecological validity of the findings. Additionally, expanding the range of pulse entropy could offer a more comprehensive understanding of the relationship between rhythmic complexity and listener responses. Moreover, including professional musicians in future studies would help determine whether rhythmic expertise influences the complexity-groove relationship.

The findings contribute to our knowledge of the relationship between musical reward and groove. Finding a rhythm-reward relationship may aid future research in a variety of fields, including social interaction and connection, as well as memory and learning. It could be relevant in future designs of active rhythm-based interventions that incorporate validated CA-BAT stimuli.

Groove's rewarding and immersive properties have the potential to be employed in conjunction with established therapeutic approaches to address mood-related problems. Furthermore, the social aspect of groove-related events might be included when studying social behavior. It may be worthwhile to investigate whether certain musical feature combinations (e.g. rhythm, harmony) can produce groove-related experiences in specific therapeutic groups, resulting in improved communication and group cohesion.

Finally, the current work added to the existing groove models. However, there may be various additional potential aspects associated with the concept of groove that future research can focus on. It may be beneficial to further research into the use of sensory-motor and social components in groove to gain a better understanding of how musical experiences are affected by both individual features and complex rhythmical patterns. Ultimately, examining groove using CA-BAT stimuli from a cultural and developmental standpoint may provide a more comprehensive knowledge of musical experience in terms of the rhythm and reward link.

8. CONCLUSION

The current study concludes that a sense of groove is associated with perceived rhythmic complexity. The findings indicate that a moderate degree of pulse entropy best predicts both pleasure and the desire to move, establishing an inverted U-shaped relationship across the CA-BAT stimuli. It emphasizes that the syncopated rhythms in the CA-BAT tracks produce an optimal level of tension between expectancy and violation, increasing enjoyment and motivation to move. Furthermore, these findings emphasize the complex ways in which multiple types of engagement (social and sensory-motor) interact with rhythmic patterns (such as pulse entropy) to influence emotional experiences like pleasure and wanting to move.The findings underscore the need to take into account specific dimensions of engagement when researching the emotional effects of rhythmic or sensory stimuli. Furthermore, it emphasizes that individual variations, such as musical training, must be taken into account when determining a preference for rhythmic complexity. These findings add to our understanding of the diverse nature of musical enjoyment and movement motivation, implying that, while some rhythmic aspects are important, the overall groove experience is determined by a broader and more complex collection of variables like musical reward. These results have potential implications for understanding how rhythmic patterns and personal characteristics interact to shape emotional and physical responses to music. Ultimately, it provides a base for the use of the stimuli for further research and potential development of novel interventions.

9. BIBLIOGRAPHY

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Usinglme4. *Journal of Statistical Software*, *67*(1). https://doi.org/10.18637/jss.v067.i01

Belfi, A. M., & Loui, P. (2019). Musical anhedonia and rewards of music listening: current advances and a proposed model. *Annals of the New York Academy of Sciences*, *1464*(1), 99–114. https://doi.org/10.1111/nyas.14241

Benson, P., Kathios, N., & Loui, P. (2024). Predictive coding in musical anhedonia: A study of groove. *PLoS ONE*, *19*(4), e0301478. https://doi.org/10.1371/journal.pone.0301478

Berlyne, D. E. (1973). Aesthetics and psychobiology. *Journal of Aesthetics and Art Criticism*, *31*(4).

Bowling, D. L., Ancochea, P. G., Hove, M. J., & Fitch, W. T. (2019). Pupillometry of Groove: Evidence for Noradrenergic Arousal in the Link Between Music and Movement. *Frontiers in Neuroscience*, *12*. https://doi.org/10.3389/fnins.2018.01039

Bowman, W. (2000). A Somatic, "Here and Now" Semantic: Music, Body, and Self. *Bulletin of the Council for Research in Music Education*, *No. 144*, 45–60.

Brown, S., & Jordania, J. (2011). Universals in the world's musics. *Psychology of Music*, *41*(2), 229–248. https://doi.org/10.1177/0305735611425896

Buhusi, C. V., & Meck, W. H. (2005). What makes us tick? Functional and neural mechanisms of interval timing. *Nature Reviews. Neuroscience*, *6*(10), 755–765. https://doi.org/10.1038/nrn1764

Câmara, G. S., & Danielsen, A. (2018). *Groove*. 270–294. https://doi.org/10.1093/oxfordhb/9780190454746.013.17

Cameron, D. J., Caldarone, N., Psaris, M., Carrillo, C., & Trainor, L. J. (2023). The complexity‐aesthetics relationship for musical rhythm is more fixed than flexible: Evidence from children and expert dancers. *Developmental Science*, *26*(5). https://doi.org/10.1111/desc.13360

Cardona, G., Ferreri, L., Lorenzo‐Seva, U., Russo, F. A., & Rodriguez‐Fornells, A. (2022). The forgotten role of absorption in music reward. *Annals of the New York Academy of Sciences*, *1514*(1), 142–154. https://doi.org/10.1111/nyas.14790

Carraturo, G., Ferreri, L., Cardona, G., Lorenzo-Seva, U., Rodriguez-Fornells, A., & Brattico, E. (2023). *The Italian Version of the extended Barcelona Music Reward Questionnaire (eBMRQ): A Validation Study and Association with Age, Gender, and Musicianship*. https://doi.org/10.31234/osf.io/a8vfc

Chen, J. L., Penhune, V. B., & Zatorre, R. J. (2008). Moving on Time: Brain Network for Auditory-Motor Synchronization is Modulated by Rhythm Complexity and Musical Training. *Journal of Cognitive Neuroscience*, *20*(2), 226–239. https://doi.org/10.1162/jocn.2008.20018

Cheung, V. K., Harrison, P. M., Meyer, L., Pearce, M. T., Haynes, J. D., & Koelsch, S. (2019). Uncertainty and Surprise Jointly Predict Musical Pleasure and Amygdala, Hippocampus, and Auditory Cortex Activity. *Current Biology*, *29*(23), 4084-4092.e4. https://doi.org/10.1016/j.cub.2019.09.067

Csikszentmihalyi, M. (1988). The flow experience and its significance for human psychology. In M. Csikszentmihalyi & I. S. Csikszentmihalyi (Eds.), Optimal experience: Psychological studies of flow in consciousness (pp. 15–35). Cambridge University Press.

Danielsen, A., Nymoen, K., Anderson, E., Câmara, G. S., Langerød, M. T., Thompson, M. R., & London, J. (2019). Where is the beat in that note? Effects of attack, duration, and frequency on the perceived timing of musical and quasi-musical sounds. *Journal of Experimental Psychology Human Perception & Performance*, *45*(3), 402–418. https://doi.org/10.1037/xhp0000611

Davies, M., Madison, G., Silva, P., & Gouyon, F. (2012). The Effect of Microtiming Deviations on the Perception of Groove in Short Rhythms. *Music Perception an Interdisciplinary Journal*, *30*(5), 497–510. https://doi.org/10.1525/mp.2013.30.5.497

Elst, O. F. V., Vuust, P., & Kringelbach, M. L. (2021). Sweet anticipation and positive emotions in music, groove, and dance. *Current Opinion in Behavioral Sciences*, *39*, 79–84. https://doi.org/10.1016/j.cobeha.2021.02.016

Erle, T. M., Reber, R., & Topolinski, S. (2017). Affect from mere perception: Illusory contour perception feels good. *Emotion*, *17*(5), 856–866. https://doi.org/10.1037/emo0000293

Etani, T., Marui, A., Kawase, S., & Keller, P. E. (2018). Optimal Tempo for Groove: Its Relation to Directions of Body Movement and Japanese nori. *Frontiers in Psychology*, *9*. https://doi.org/10.3389/fpsyg.2018.00462

Etani, T., Miura, A., Kawase, S., Fujii, S., Keller, P. E., Vuust, P., & Kudo, K. (2024). A review of psychological and neuroscientific research on musical groove. *Neuroscience & Biobehavioral Reviews*, *158*, 105522. https://doi.org/10.1016/j.neubiorev.2023.105522

Ferreri, L., Mas-Herrero, E., Zatorre, R. J., Ripollés, P., Gomez-Andres, A., Alicart, H., Olivé, G., Marco-Pallarés, J., Antonijoan, R. M., Valle, M., Riba, J., & Rodriguez-Fornells, A. (2019). Dopamine modulates the reward experiences elicited by music. *Proceedings of* *the National Academy of Sciences*, *116*(9), 3793–3798. https://doi.org/10.1073/pnas.1811878116

Fincher-Kiefer, R. (2019). How the body shapes knowledge: Empirical support for embodied cognition. In *American Psychological Association eBooks*. https://doi.org/10.1037/0000136-000

Fitch, W. T., & Rosenfeld, A. J. (2007). Perception and Production of Syncopated Rhythms. *Music Perception an Interdisciplinary Journal*, *25*(1), 43–58. https://doi.org/10.1525/mp.2007.25.1.43

Fiveash, A., Ferreri, L., Bouwer, F., Kösem, A., Moghimi, S., Ravignani, A., Keller, P., & Tillmann, B. (2023). Can rhythm-mediated reward boost learning, memory, and social connection? Perspectives for future research. *Neuroscience & Biobehavioral Reviews*, *149*, 105153. https://doi.org/10.1016/j.neubiorev.2023.105153

Frühauf, J., Kopiez, R., & Platz, F. (2013). Music on the timing grid: The influence of microtiming on the perceived groove quality of a simple drum pattern performance. *Musicae Scientiae*, *17*(2), 246–260. https://doi.org/10.1177/1029864913486793

Fukuie, T., Suwabe, K., Kawase, S., Shimizu, T., Ochi, G., Kuwamizu, R., Sakairi, Y., & Soya, H. (2022). Groove rhythm stimulates prefrontal cortex function in groove enjoyers. *Scientific Reports*, *12*(1). https://doi.org/10.1038/s41598-022-11324-3

Heyduk, R. G. (1975). Rated preference for musical compositions as it relates to complexity and exposure frequency. *Perception & Psychophysics*, *17*, 84-90.

Hurley, B. K., Martens, P. A., & Janata, P. (2014). Spontaneous sensorimotor coupling with multipart music. *Journal of Experimental Psychology Human Perception & Performance*, *40*(4), 1679–1696. https://doi.org/10.1037/a0037154

Huron, D. (2006). Sweet Anticipation. In *The MIT Press eBooks*. https://doi.org/10.7551/mitpress/6575.001.0001

Iversen, J. R., & Patel, A. D. (2008). The Beat Alignment Test (BAT): Surveying beat processing abilities in the general population.

Gabrielsson, A., & Lindström, E. (1993). The Role of Structure in the Musical Expression of Emotions. In *Oxford University Press eBooks* (pp. 367–400). https://doi.org/10.1093/acprof:oso/9780199230143.003.0014

Gebauer, L., Kringelbach, M. L., & Vuust, P. (2012). Ever-changing cycles of musical pleasure: The role of dopamine and anticipation. *Psychomusicology Music Mind and Brain*, *22*(2), 152–167. https://doi.org/10.1037/a0031126

Gold, B. P., Pearce, M. T., Mas-Herrero, E., Dagher, A., & Zatorre, R. J. (2019). Predictability and Uncertainty in the Pleasure of Music: A Reward for Learning? *Journal of Neuroscience*, *39*(47), 9397–9409. https://doi.org/10.1523/jneurosci.0428-19.2019

Gonzalez-Sanchez, V. E., Zelechowska, A., & Jensenius, A. R. (2018). Correspondences Between Music and Involuntary Human Micromotion During Standstill. *Frontiers in Psychology*, *9*. https://doi.org/10.3389/fpsyg.2018.01382

Gordon, C. L., Cobb, P. R., & Balasubramaniam, R. (2018). Recruitment of the motor system during music listening: An ALE meta-analysis of fMRI data. *PLoS ONE*, *13*(11), e0207213. https://doi.org/10.1371/journal.pone.0207213

Goupil, L., & Aucouturier, J. J. (2019). Musical pleasure and musical emotions. *Proceedings of the National Academy of Sciences*, *116*(9), 3364–3366. https://doi.org/10.1073/pnas.1900369116

Gundlach, R. H. (1935). Factors Determining the Characterization of Musical Phrases. *The American Journal of Psychology*, *47*(4), 624. https://doi.org/10.2307/1416007

Grahn, J. A. (2009). The Role of the Basal Ganglia in Beat Perception. *Annals of the New York Academy of Sciences*, *1169*(1), 35–45. https://doi.org/10.1111/j.1749-6632.2009.04553.x

Grahn, J. A. (2012). Neural Mechanisms of Rhythm Perception: Current Findings and Future Perspectives. *Topics in Cognitive Science*, *4*(4), 585–606. https://doi.org/10.1111/j.1756-8765.2012.01213.x

Handel, S. (1989). Listening: An introduction to the perception of auditory events. Cambridge, MA: MIT Press.

Hannon, E. E., Soley, G., & Ullal, S. (2012). Familiarity overrides complexity in rhythm perception: A cross-cultural comparison of American and Turkish listeners. *Journal of Experimental Psychology Human Perception & Performance*, *38*(3), 543–548. https://doi.org/10.1037/a0027225

Harrison, P. M. C., & Müllensiefen, D. (2018). Development and Validation of the Computerised Adaptive Beat Alignment Test (CA-BAT). *Scientific Reports*, *8*(1). https://doi.org/10.1038/s41598-018-30318-8

Janata, P., Tomic, S. T., & Haberman, J. M. (2012). Sensorimotor coupling in music and the psychology of the groove. *Journal of Experimental Psychology General*, *141*(1), 54–75. https://doi.org/10.1037/a0024208

Jones, M. R. (1976). Time, our lost dimension: Toward a new theory of perception, attention, and memory. *Psychological Review*, *83*(5), 323–355. https://doi.org/10.1037/0033-295x.83.5.323

Jones, M. R., & Boltz, M. (1989). Dynamic attending and responses to time. *Psychological Review*, *96*(3), 459–491. https://doi.org/10.1037/0033-295x.96.3.459

Juslin, P. N., Liljeström, S., Västfjäll, D., & Lundqvist, L. O. (1993). How Does Music Evoke Emotions? In *Oxford University Press eBooks* (pp. 605–642). https://doi.org/10.1093/acprof:oso/9780199230143.003.0022

Juslin, P. N. (2013). From everyday emotions to aesthetic emotions: Towards a unified theory of musical emotions. *Physics of Life Reviews*, *10*(3), 235–266. https://doi.org/10.1016/j.plrev.2013.05.008

Kaeppler, A. L. (2000). Dance Ethnology and the Anthropology of Dance. *Dance Research Journal*, *32*(1), 116. https://doi.org/10.2307/1478285

Kathios, N., Patel, A. D., & Loui, P. (2024). Musical anhedonia, timbre, and the rewards of music listening. *Cognition*, *243*, 105672. https://doi.org/10.1016/j.cognition.2023.105672

Keller, P. E., & Schubert, E. (2011). Cognitive and affective judgements of syncopated musical themes. *Advances in Cognitive Psychology*, *7*(1), 142–156. https://doi.org/10.2478/v10053-008-0094-0

Keil, Charles & Feld, Steven (2005). Music Grooves: Essays and Dialogues. *Fenestra Books.*

Koelsch, S., Vuust, P., & Friston, K. (2019). Predictive Processes and the Peculiar Case of Music. *Trends in Cognitive Sciences*, *23*(1), 63–77. https://doi.org/10.1016/j.tics.2018.10.006

Kornysheva, K., Von Cramon, D. Y., Jacobsen, T., & Schubotz, R. I. (2009). Tuning-in to the beat: Aesthetic appreciation of musical rhythms correlates with a premotor activity boost. *Human Brain Mapping*, *31*(1), 48–64. https://doi.org/10.1002/hbm.20844

Kraus, N., & Hesselmann, G. (2021). Musicality as a predictive process. *Behavioral and Brain Sciences*, *44*. https://doi.org/10.1017/s0140525x20000746

Ladinig, O., Honing, H., Háden, G., & Winkler, I. (2009). Probing Attentive and Preattentive Emergent Meter in Adult Listeners without Extensive Music Training. *Music Perception an Interdisciplinary Journal*, *26*(4), 377–386. https://doi.org/10.1525/mp.2009.26.4.377

Lakatos, P., Karmos, G., Mehta, A. D., Ulbert, I., & Schroeder, C. E. (2008). Entrainment of Neuronal Oscillations as a Mechanism of Attentional Selection. *Science*, *320*(5872), 110–113. https://doi.org/10.1126/science.1154735

Lakatos, P., Musacchia, G., O'Connel, M. N., Falchier, A. Y., Javitt, D. C., & Schroeder, C. E. (2013). The Spectrotemporal Filter Mechanism of Auditory Selective Attention. *Neuron*, *77*(4), 750–761. https://doi.org/10.1016/j.neuron.2012.11.034

Large, E. W., & Jones, M. R. (1999). The dynamics of attending: How people track time-varying events. *Psychological Review*, *106*(1), 119–159. https://doi.org/10.1037/0033-295x.106.1.119

Large, E. W., Herrera, J. A., & Velasco, M. J. (2015). Neural Networks for Beat Perception in Musical Rhythm. *Frontiers in Systems Neuroscience*, *9*. https://doi.org/10.3389/fnsys.2015.00159

Large, E. W., & Snyder, J. S. (2009). Pulse and Meter as Neural Resonance. *Annals of the New York Academy of Sciences*, *1169*(1), 46–57. https://doi.org/10.1111/j.1749-6632.2009.04550.x

Lartillot, O., Eerola, T., Toiviainen, P., & Fornari, J. (2008). *Multi-Feature Modeling of Pulse Clarity: Design, Validation and Optimization*.

Leman, M., & Maes, P. J. (2015). The Role of Embodiment in the Perception of Music. *Empirical Musicology Review*, *9*(3–4), 236–246. https://doi.org/10.18061/emr.v9i3-4.4498

London, J. (2012). *Hearing in Time: Psychological Aspects of Musical Meter*, 2nd ed. Oxford University Press. https://doi.org/10.1093/acprof:oso/9780199744374.001.0001

Longuet-Higgins, H. C., & Lee, C. S. (1984). The Rhythmic Interpretation of Monophonic Music. *Music Perception an Interdisciplinary Journal*, *1*(4), 424–441. https://doi.org/10.2307/40285271

Loui, P., Patterson, S., Sachs, M. E., Leung, Y., Zeng, T., & Przysinda, E. (2017). White Matter Correlates of Musical Anhedonia: Implications for Evolution of Music. *Frontiers in Psychology*, *8*. https://doi.org/10.3389/fpsyg.2017.01664

Lüdecke, D., Ben-Shachar, M., Patil, I., Waggoner, P., & Makowski, D. (2021). performance: An R Package for Assessment, Comparison and Testing of Statistical Models. *The Journal of Open Source Software*, *6*(60), 3139. https://doi.org/10.21105/joss.03139

Lumaca, M., Haumann, N. T., Brattico, E., Grube, M., & Vuust, P. (2019). Weighting of neural prediction error by rhythmic complexity: A predictive coding account using mismatch negativity. *European Journal of Neuroscience*, *49*(12), 1597–1609. https://doi.org/10.1111/ejn.14329

Madison, G. (2001). Different kinds of groove in jazz and dance music as indicated by listeners' ratings. *Proceedings of the VII International Symposium on Systematic and Comparative Musicology and III International Conference on Cognitive Musicology / [Ed] Henna Lapalainen, Jyväskylä: University of Jyväskylä,* 108–112.

Madison, G. (2006). Experiencing Groove Induced by Music: Consistency and Phenomenology. *Music Perception an Interdisciplinary Journal*, *24*(2), 201–208. https://doi.org/10.1525/mp.2006.24.2.201

Madison, G., Gouyon, F., Ullén, F., & Hörnström, K. (2011). Modeling the tendency for music to induce movement in humans: First correlations with low-level audio descriptors across music genres. *Journal of Experimental Psychology Human Perception & Performance*, *37*(5), 1578–1594. https://doi.org/10.1037/a0024323

Madison, G., & Sioros, G. (2014). What musicians do to induce the sensation of groove in simple and complex melodies, and how listeners perceive it. *Frontiers in Psychology*, *5*. https://doi.org/10.3389/fpsyg.2014.00894

Manzara, L. C., Witten, I. H., & James, M. (1992). On the Entropy of Music: An Experiment with Bach Chorale Melodies. *Leonardo Music Journal*, *2*(1), 81. https://doi.org/10.2307/1513213

Margulis, E. H., & Beatty, A. P. (2008). Musical Style, Psychoaesthetics, and Prospects for Entropy as an Analytic Tool. *Computer Music Journal*, *32*(4), 64–78. https://doi.org/10.1162/comj.2008.32.4.64

Martínez-Molina, N., Mas-Herrero, E., Rodríguez-Fornells, A., Zatorre, R. J., & Marco-Pallarés, J. (2016). Neural correlates of specific musical anhedonia. *Proceedings of the National Academy of Sciences*, *113*(46). https://doi.org/10.1073/pnas.1611211113

Mas-Herrero, E., Karhulahti, M., Marco-Pallares, J., Zatorre, R. J., & Rodriguez-Fornells, A. (2018). The impact of visual art and emotional sounds in specific musical anhedonia. *Progress in Brain Research*, 399–413. https://doi.org/10.1016/bs.pbr.2018.03.017

Mas-Herrero, E., Marco-Pallares, J., Lorenzo-Seva, U., Zatorre, R. J., & Rodriguez-Fornells, A. (2012). Individual Differences in Music Reward Experiences. *Music Perception an Interdisciplinary Journal*, *31*(2), 118–138. https://doi.org/10.1525/mp.2013.31.2.118

Mas-Herrero, E., Zatorre, R. J., Rodriguez-Fornells, A., & Marco-Pallarés, J. (2014). Dissociation between Musical and Monetary Reward Responses in Specific Musical Anhedonia. *Current Biology*, *24*(6), 699–704. https://doi.org/10.1016/j.cub.2014.01.068

Matthews, T. E., Witek, M. A. G., Heggli, O. A., Penhune, V. B., & Vuust, P. (2019). The sensation of groove is affected by the interaction of rhythmic and harmonic complexity. *PLoS ONE*, *14*(1), e0204539. https://doi.org/10.1371/journal.pone.0204539

Matthews, T. E., Witek, M. A., Lund, T., Vuust, P., & Penhune, V. B. (2020). The sensation of groove engages motor and reward networks. *NeuroImage*, *214*, 116768. https://doi.org/10.1016/j.neuroimage.2020.116768

Matthews, T. E., Witek, M. A. G., Thibodeau, J. L. N., Vuust, P., & Penhune, V. B. (2022). Perceived Motor Synchrony With the Beat is More Strongly Related to Groove Than Measured Synchrony. *Music Perception an Interdisciplinary Journal*, *39*(5), 423–442. https://doi.org/10.1525/mp.2022.39.5.423

McAuley, J. D. (2010). Tempo and Rhythm. In *Springer handbook of auditory research* (pp. 165–199). https://doi.org/10.1007/978-1-4419-6114-3_6

McNamara, L., & Ballard, M. E. (1999). Resting arousal, sensation seeking, and music preference. *Genetic, Social, and General Psychology Monographs*, *125*(3), 229.

Mehr, S. A., Singh, M., Knox, D., Ketter, D. M., Pickens-Jones, D., Atwood, S., Lucas, C., Jacoby, N., Egner, A. A., Hopkins, E. J., Howard, R. M., Hartshorne, J. K., Jennings, M. V., Simson, J., Bainbridge, C. M., Pinker, S., O'Donnell, T. J., Krasnow, M. M., & Glowacki, L. (2019). Universality and diversity in human song. *Science*, *366*(6468). https://doi.org/10.1126/science.aax0868

Meyer, L.B. (1956). *Emotion and meaning in music.* University of Chicago Press: Chicago.

Müllensiefen, D., Gingras, B., Musil, J., & Stewart, L. (2014). The Musicality of Non-Musicians: An Index for Assessing Musical Sophistication in the General Population. *PLoS ONE*, *9*(2), e89642. https://doi.org/10.1371/journal.pone.0089642

Müllensiefen, D., Gingras, B., Stewart, L., & Musil, J. J. (2013). *Goldsmiths Musical Sophistication Index (Gold-MSI) v1.0: Technical Report and Documentation*.

Nakagawa, S., & Schielzeth, H. (2013). A general and simple method for obtaining R2 from generalized linear mixed‐effects models. *Methods in Ecology and Evolution*, *4*(2), 133–142. https://doi.org/10.1111/j.2041-210x.2012.00261.x

Nettl, B. (1999). An Ethnomusicologist Contemplates Universals in Musical Sound and Musical Culture. In *The MIT Press eBooks* (pp. 463–472). https://doi.org/10.7551/mitpress/5190.003.0032

Nobre, A. C., & Van Ede, F. (2017). Anticipated moments: temporal structure in attention. *Nature Reviews. Neuroscience*, *19*(1), 34–48. https://doi.org/10.1038/nrn.2017.141

North, A. C., & Hargreaves, D. J. (1995). Subjective complexity, familiarity, and liking for popular music. *Psychomusicology* 14: 77–93.

North, A. C., & Hargreaves, D. J. (1997). Experimental aesthetics and everyday music listening. In: Hargreaves DJ, North AC, editors. The social psychology of music. Oxford: Oxford University Press.

North, A. C., & Hargreaves, D. J. (1998). Complexity, propotypicality, familiarity, and the perception of musical quality. *Psychomusicology* 17: 77–80.

Nozaradan, S., Schwartze, M., Obermeier, C., & Kotz, S. A. (2017). Specific contributions of basal ganglia and cerebellum to the neural tracking of rhythm. *Cortex*, *95*, 156–168. https://doi.org/10.1016/j.cortex.2017.08.015

Obleser, J., & Kayser, C. (2019). Neural Entrainment and Attentional Selection in the Listening Brain. *Trends in Cognitive Sciences*, *23*(11), 913–926. https://doi.org/10.1016/j.tics.2019.08.004

O'Connell, S. R., Nave-Blodgett, J. E., Wilson, G. E., Hannon, E. E., & Snyder, J. S. (2022). Elements of musical and dance sophistication predict musical groove perception. *Frontiers in Psychology*, *13*. https://doi.org/10.3389/fpsyg.2022.998321

Orr, M. G., & Ohlsson, S. (2005). Relationship between complexity and liking as a function of expertise. *Music Perception*, *22*(4), 583-611.

Peirce, J. W. (2007). PsychoPy—Psychophysics software in Python. *Journal of Neuroscience Methods*, *162*(1–2), 8–13. https://doi.org/10.1016/j.jneumeth.2006.11.017

Peirce, J. W. (2009). Generating stimuli for neuroscience using PsychoPy. *Frontiers in Neuroinformatics*, *2*. https://doi.org/10.3389/neuro.11.010.2008

Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., Kastman, E., & Lindeløv, J. K. (2019). PsychoPy2: Experiments in behavior made easy. *Behavior Research Methods*, *51*(1), 195–203. https://doi.org/10.3758/s13428-018-01193-y

Phillips-Silver, J., & Trainor, L. J. (2005). Feeling the Beat: Movement Influences Infant Rhythm Perception. *Science*, *308*(5727), 1430. https://doi.org/10.1126/science.1110922

Romkey, I. D., Matthews, T., Foster, N. E. V., Bella, S. D., & Penhune, V. (2024). *The Pleasurable Urge to Move to Music is Unchanged in Musical Anhedonia*. https://doi.org/10.31234/osf.io/7envx

Roncaglia-Denissen, M. P., Schmidt-Kassow, M., Heine, A., Vuust, P., & Kotz, S. A. (2013). Enhanced musical rhythmic perception in Turkish early and late learners of German. *Frontiers in Psychology*, *4*. https://doi.org/10.3389/fpsyg.2013.00645

Rickard, N. S. (2004). Intense emotional responses to music: a test of the physiological arousal hypothesis. *Psychology of Music*, *32*(4), 371–388. https://doi.org/10.1177/0305735604046096

Pressing, J. (2002). Black Atlantic Rhythm: Its Computational and Transcultural Foundations. *Music Perception an Interdisciplinary Journal*, *19*(3), 285–310. https://doi.org/10.1525/mp.2002.19.3.285

R Core Team (2023) R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna. https://www.R-project.org/

Repp, B. H., & Su, Y. H. (2013). Sensorimotor synchronization: A review of recent research (2006–2012). *Psychonomic Bulletin & Review*, *20*(3), 403–452. https://doi.org/10.3758/s13423-012-0371-2

Ross, J. M., Warlaumont, A. S., Abney, D. H., Rigoli, L. M., & Balasubramaniam, R. (2016). Influence of musical groove on postural sway. *Journal of Experimental Psychology Human Perception & Performance*, *42*(3), 308–319. https://doi.org/10.1037/xhp0000198

Russo, F. (2018). *Multisensory Processing in Music*. 211–234. https://doi.org/10.1093/oxfordhb/9780198804123.013.10

Salimpoor, V. N., Benovoy, M., Larcher, K., Dagher, A., & Zatorre, R. J. (2011). Anatomically distinct dopamine release during anticipation and experience of peak emotion to music. *Nature Neuroscience*, *14*(2), 257–262. https://doi.org/10.1038/nn.2726

Salimpoor, V. N., Zald, D. H., Zatorre, R. J., Dagher, A., & McIntosh, A. R. (2015). Predictions and the brain: how musical sounds become rewarding. *Trends in Cognitive Sciences*, *19*(2), 86–91. https://doi.org/10.1016/j.tics.2014.12.001

Savage, P. E., Brown, S., Sakai, E., & Currie, T. E. (2015). Statistical universals reveal the structures and functions of human music. *Proceedings of the National Academy of Sciences*, *112*(29), 8987–8992. https://doi.org/10.1073/pnas.1414495112

Savage, P. E., Loui, P., Tarr, B., Schachner, A., Glowacki, L., Mithen, S., & Fitch, W. T. (2020). Music as a coevolved system for social bonding. Behavioral and Brain Sciences, 44. https://doi.org/10.1017/s0140525x20000333

Senn, O., Bechtold, T., Rose, D., Câmara, G. S., Düvel, N., Jerjen, R., Kilchenmann, L., Hoesl, F., Baldassarre, A., & Alessandri, E. (2020). Experience of Groove Questionnaire. *Music Perception an Interdisciplinary Journal*, *38*(1), 46–65. https://doi.org/10.1525/mp.2020.38.1.46

Senn, O., Kilchenmann, L., Bechtold, T., & Hoesl, F. (2018). Groove in drum patterns as a function of both rhythmic properties and listeners' attitudes. *PLoS ONE*, *13*(6), e0199604. https://doi.org/10.1371/journal.pone.0199604

Senn, O., Kilchenmann, L., Von Georgi, R., & Bullerjahn, C. (2016). The Effect of Expert Performance Microtiming on Listeners' Experience of Groove in Swing or Funk Music. *Frontiers in Psychology*, *7*. https://doi.org/10.3389/fpsyg.2016.01487

Senn, O., Rose, D., Bechtold, T., Kilchenmann, L., Hoesl, F., Jerjen, R., Baldassarre, A., & Alessandri, E. (2019). Preliminaries to a Psychological Model of Musical Groove. *Frontiers in Psychology*, *10*. https://doi.org/10.3389/fpsyg.2019.01228

Shapiro, L. (2019). Embodied Cognition. In *Routledge eBooks*. https://doi.org/10.4324/9781315180380

Sioros, G., Miron, M., Davies, M., Gouyon, F., & Madison, G. (2014). Syncopation creates the sensation of groove in synthesized music examples. *Frontiers in Psychology*, *5*. https://doi.org/10.3389/fpsyg.2014.01036

Song, C., Simpson, A. J. R., Harte, C. A., Pearce, M. T., & Sandler, M. B. (2013). Syncopation and the Score. *PLoS ONE*, *8*(9), e74692. https://doi.org/10.1371/journal.pone.0074692

Spiech, C., Hope, M., Guilherme, S. C., Sioros, G., Endestad, T., Laeng, B., & Danielsen, A. (2022). Sensorimotor Synchronization Increases Groove. *Zenodo (CERN European Organization for Nuclear Research)*. https://doi.org/10.5281/zenodo.6908099

Spiech, C., Sioros, G., Endestad, T., Danielsen, A., & Laeng, B. (2022). Pupil drift rate indexes groove ratings. *Scientific Reports*, *12*(1). https://doi.org/10.1038/s41598-022-15763-w

Stupacher, J., Hove, M. J., Novembre, G., Schütz-Bosbach, S., & Keller, P. E. (2013). Musical groove modulates motor cortex excitability: A TMS investigation. *Brain and Cognition*, *82*(2), 127–136. https://doi.org/10.1016/j.bandc.2013.03.003

Stupacher, J., Matthews, T. E., Pando-Naude, V., Elst, O. F. V., & Vuust, P. (2022). The sweet spot between predictability and surprise: musical groove in brain, body, and social interactions. *Frontiers in Psychology*, *13*. https://doi.org/10.3389/fpsyg.2022.906190

Tarr, B., Launay, J., & Dunbar, R. I. M. (2014). Music and social bonding: "self-other" merging and neurohormonal mechanisms. Frontiers in Psychology, 5. https://doi.org/10.3389/fpsyg.2014.01096

Teki, S., Grube, M., & Griffiths, T. D. (2012). A Unified Model of Time Perception Accounts for Duration-Based and Beat-Based Timing Mechanisms. *Frontiers in Integrative Neuroscience*, *5*. https://doi.org/10.3389/fnint.2011.00090

Temperley, D. (2010). Modeling Common-Practice Rhythm. *Music Perception an Interdisciplinary Journal*, *27*(5), 355–376. https://doi.org/10.1525/mp.2010.27.5.355

Thaut, M. H., Demartin, M., & Sanes, J. N. (2008). Brain Networks for Integrative Rhythm Formation. *PLoS ONE*, *3*(5), e2312. https://doi.org/10.1371/journal.pone.0002312

Thul, E., & Toussaint, G. T. (2008). Rhythm Complexity Measures: A Comparison of Mathematical Models of Human Perception and Performance. In *ISMIR* (pp. 663-668).

Toussaint, G. T. (2019). *The geometry of musical rhythm: what makes a" good" rhythm good?*. CRC Press.

Trost, W., & Vuilleumier, P. (2013). Rhythmic entrainment as a mechanism for emotion induction by music. In *Oxford University Press eBooks* (pp. 213–225). https://doi.org/10.1093/acprof:oso/9780199654888.003.0016

Trost, W. J., Labbé, C., & Grandjean, D. (2017). Rhythmic entrainment as a musical affect induction mechanism. *Neuropsychologia*, *96*, 96–110. https://doi.org/10.1016/j.neuropsychologia.2017.01.004

Trost, W., Frühholz, S., Schön, D., Labbé, C., Pichon, S., Grandjean, D., & Vuilleumier, P. (2014). Getting the beat: Entrainment of brain activity by musical rhythm and pleasantness. *NeuroImage*, *103*, 55–64. https://doi.org/10.1016/j.neuroimage.2014.09.009

Varela, F. J., Thompson, E., Rosch, E., & Kabat-Zinn, J. (2017). *The Embodied Mind*. https://doi.org/10.7551/mitpress/9780262529365.001.0001

Vuust, P., Dietz, M. J., Witek, M., & Kringelbach, M. L. (2018). Now you hear it: a predictive coding model for understanding rhythmic incongruity. *Annals of the New York Academy of Sciences*, *1423*(1), 19–29. https://doi.org/10.1111/nyas.13622

Vuust, P., & Frith, C. D. (2008). Anticipation is the key to understanding music and the effects of music on emotion. *Behavioral and Brain Sciences*, *31*(5), 599–600. https://doi.org/10.1017/s0140525x08005542

Vuust, P., Heggli, O. A., Friston, K. J., & Kringelbach, M. L. (2022). Music in the brain. *Nature Reviews. Neuroscience*, *23*(5), 287–305. https://doi.org/10.1038/s41583-022-00578-5

Vuust, P., Ostergaard, L., Pallesen, K. J., Bailey, C., & Roepstorff, A. (2009). Predictive coding of music – Brain responses to rhythmic incongruity. *Cortex*, *45*(1), 80–92. https://doi.org/10.1016/j.cortex.2008.05.014

Vuust, P., & Witek, M. a. G. (2014). Rhythmic complexity and predictive coding: a novel approach to modeling rhythm and meter perception in music. *Frontiers in Psychology*, *5*. https://doi.org/10.3389/fpsyg.2014.01111

Wesolowski, B. C., & Hofmann, A. (2016). There's More to Groove than Bass in Electronic Dance Music: Why Some People Won't Dance to Techno. PLoS ONE, 11(10), e0163938. https://doi.org/10.1371/journal.pone.0163938

Witek, M. A. G. (2016). Filling In: Syncopation, Pleasure and Distributed Embodiment in Groove. *Music Analysis*, *36*(1), 138–160. https://doi.org/10.1111/musa.12082

Witek, M. A. G., Clarke, E. F., Wallentin, M., Kringelbach, M. L., & Vuust, P. (2014). Syncopation, Body-Movement and Pleasure in Groove Music. PLoS ONE, 9(4), e94446. https://doi.org/10.1371/journal.pone.0094446

Witek, M. A. G., Liu, J., Kuubertzie, J., Yankyera, A. P., Adzei, S., & Vuust, P. (2020). A Critical Cross-cultural Study of Sensorimotor and Groove Responses to Syncopation Among Ghanaian and American University Students and Staff. *Music Perception an Interdisciplinary Journal*, *37*(4), 278–297. https://doi.org/10.1525/mp.2020.37.4.278

Witek, M. A. G., Popescu, T., Clarke, E. F., Hansen, M., Konvalinka, I., Kringelbach, M. L., & Vuust, P. (2016). Syncopation affects free body-movement in musical groove. *Experimental Brain Research*, *235*(4), 995–1005. https://doi.org/10.1007/s00221-016-4855-6

Wundt, W. (1874). Grundzüge der Physiologischen Psychologie. Leipzig: Wilhelm Engelmann.

Zald, D. H., & Zatorre, R. J. (2011). *Music*. Neurobiology of Sensation and Reward - NCBI Bookshelf. https://www.ncbi.nlm.nih.gov/books/NBK92781/

Zatorre, R. J. (2015). Musical pleasure and reward: mechanisms and dysfunction. Annals of the New York Academy of Sciences, 1337(1), 202–211. https://doi.org/10.1111/nyas.12677

Zelechowska, A., Gonzalez-Sanchez, V. E., Laeng, B., & Jensenius, A. R. (2020). Headphones or Speakers? An Exploratory Study of Their Effects on Spontaneous Body Movement to Rhythmic Music. *Frontiers in Psychology*, *11*. https://doi.org/10.3389/fpsyg.2020.00698

10. APPENDICES

CA-BAT tracks and their Pulse Entropy values

	Track	***Pulse Entropy***
1.	boabab.5sec.wav	0.7405
2.	crazy.5sec.wav	0.72017
3.	creation.5sec.wav	0.76668
4.	devil.5sec.wav	0.74866
5.	dusk.5sec.wav	0.76938
6.	espionage.5sec.wav	0.77558
7.	freedom.5sec.wav	0.71338
8.	galactic.5sec.wav	0.76101
9.	good1.5sec.wav	0.77926
10.	good2.5sec.wav	0.72362
11.	hedgehog.5sec.wav	0.72609
12.	heroes.5sec.wav	0.8151
13.	ice.5sec.wav	0.79261
14.	king.5sec.wav	0.78518
15.	lark.5sec.wav	0.73635
16.	lord.5sec.wav	0.79748
17.	lori.5sec.wav	0.75384

18.	neural.5sec.wav	0.73468
19.	never.5sec.wav	0.73413
20.	new.5sec.wav	0.80393
21.	one.5sec.wav	0.7394
22.	prime.5sec.wav	0.71876
23.	psychedelic.5sec.wav	0.76286
24.	roaring.5sec.wav	0.76291
25.	rustic.5sec.wav	0.80325
26.	sassy.5sec.wav	0.72234
27.	secret.5sec.wav	0.81131
28.	shadow.5sec.wav	0.72848
29.	shock.5sec.wav	0.78512
30.	spats.5sec.wav	0.78652
31.	strad.5sec.wav	0.77586
32.	sweetheart.5sec.wav	0.7317
33.	switch.5sec.wav	0.74838
34.	tarantella.5sec.wav	0.71347
35.	terminator.5sec.wav	0.80369
36.	terror.5sec.wav	0.70696
37.	trigger.5sec.wav	0.721
38.	way.5sec.wav	0.78318