Temporal Hierarchies in Music and Neural Timing: An Exploratory Review

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ABSTRACT

Predictive, hierarchical relationships in temporal experience are fundamental aspects of both music and language—vehicles of communication essential to human social bonding and survival. This exploratory review considers music as a lens through which to explore neural timing, examining research in music cognition spanning four decades. The paper describes and synthesizes findings on how humans track, predict, and actively respond to hierarchical temporal structures in music, considering what these layered, multisensory mechanisms can reveal about human cognition and communication on a broad level. A limitation to this exploration, albeit relevant in conveying the material to the reader unfamiliar with the field, is the concept of "groove" as an overarching construct. The study aims to employ more precise terminology to accurately capture the subject of interest. Additionally, it is proposed that future music cognition investigations prioritize (1) ecologically valid designs supporting naturalistic social interactions; (2) whole-body movement as central to temporal perception; and (3) multisensory integration. These considerations situate music cognition research in a meaningful position for translatable, interdisciplinary and cross-cultural application, contributing to a greater understanding of the multimodal, temporal underpinnings that support human communication.

Introduction

Predictive, hierarchical relationships in temporal experience are fundamental aspects of music and language, serving as ubiquitous vehicles of communication, essential in facilitating social bonding and survival. Through these neural processes, complex information is integrated across multimodal systems (e.g., auditory, visual, vestibular, kinesthetic, and motor), contributing to the perception and production of temporally-bound stimuli. Successful perception, expression, and information exchange hinges on the ability to process, produce, and synchronize multiple streams of information that are, at their core, rhythmic. Using music as a lens through which to explore neural timing and temporal processing provides a useful perspective in the understanding of these hierarchical frameworks in an effort to advance research on human communication and cognition.

The time aspect of music—involving beat, meter, rhythm, attending, and entrainment—may be described as event-based phenomena eliciting predictive oscillatory processes in the listener: a temporal concern. This review conducts an exploration of time- and event-based investigations of music cognition across fourteen works and several decades of research. Studies were selected based on their focus on temporal processing in music cognition as identified through literary review and research in an independent study conducted at Middle Tennessee State University (MTSU) in Summer 2025, with one additional study conducted in Winter 2026. Selection prioritized empirical studies of rhythm, meter, beat perception, and temporal attention, alongside foundational theoretical works in music cognition. The intention of this review is to synthesize investigations of temporal processing in music cognition, identify limitations in current music science approaches (particularly, the repeated use of "groove" as a catch-all construct), and consider a framework for future directions in music science that can prove translatable in the interdisciplinary study of language and communication.

Table 1: Comparison of published works explored in this literature review

Author	Year	Design	N =	Form
Desain and Honing	1989	Theoretical Model	N/A	Article
Duman et al.	2024	Experimental Design	88	Article
Henry et al.	2025	Registered Replication	60	Article
Hickock et al.	2015	Experimental Design (2)	5; 3	Article
Huron	2006	Meta Analyses, Theoretical Exploration	N/A	Book
Kalender et al.	2012	Experimental Design	56	Article
London	2004	Meta Analyses, Theoretical Exploration	N/A	Book
Palmer	1996	Case Study	1	Article
Povel and Essens	1985	Experimental Design, Theoretical Model	N/A	Article
Jones et al.	2002	Experimental Design (3)	21; 21; 11	Article
Spiech et al.	2024	Experimental Design	30	Article
Stupacher et al.	2025	Experimental Design	35	Article
Witek et al.	2014	Experimental Design	66	Article
Wu et al.	2025	Experimental Design (4)	30; 30; 31; 32	Article

Within the fourteen works reviewed, all of which were directed towards audiences within areas of music theory, music psychology, or cognitive neuroscience of music, a variety of experimental designs were used. As shown in Table 1, three of the included works were theoretical or written as meta-analyses, eleven of the works were experimental studies (including one registered replication study and one case study) with stated hypotheses, methodology, procedures, and reported findings. The experimental studies ranged from a single case study to an online study with 88 participants in total. These publications spanned many topics involving investigation of music theory and expressive choice (Palmer, 1996), psychology of musical expectation (Huron, 2006), a study of rhythmic entrainment and perceptual oscillations with a follow-up registered replication study reporting countering results (Hickok et al., 2015; Henry et al., 2025), perception of musical meter (Kalender et al., 2012; London, 2004; Povel & Essens, 1985), dynamic attending (Jones et al., 2002), computational modeling methods representative of musical time (Desain & Honing, 1989), eye blinks synchronizing to the beat as a biobehavioral marker of temporal attending while listening to music (Wu et al., 2025), and experimental studies investigating concepts related to movement, "groove," and syncopation (Duman et al., 2024; Spiech et al., 2024; Stupacher et al., 2025; Witek et al., 2014).

The scientific literature within this review exploring "groove," defined as "the pleasurable urge to move to music," (Janata et al., 2012), investigates different facets of the described phenomenon through the lens of cognitive neuroscience, clinical application in substance abuse disorders, and a redefining of the concept (Janata et al., 2012; Duman et al., 2024; Spiech et al., 2024; Stupacher et al., 2025). As psychological investigations of this concept are synthesized, "groove" as it is typically defined serves to be a useful paradigm for music science investigations. However, there is ambiguity in the term's meaning, complicating its use in scientific studies (Duman et al., 2024). Nuanced meanings of the term "groove" may be particularly unique to different generations, cultural groups, or professions (e.g., professional musicians). These inconsistencies complicate data collection, interpretation of results, and communication of findings, further narrowing the potential investigations of the multilayered, complex rhythmic and oscillatory phenomena of interest. As this review explores various facets of rhythm, meter, and temporal perception in music, I critically examine the "groove" and propose a more precise and integrated terminology.

Investigating Musical Notation and Expressive Choice

As a starting framework, consider how humans superimpose expressive choices and patterns on music as they perform, as is the case in Palmer's 1996 case study. This study utilizes statistical analyses to disentangle expressive performance choices made by an expert performer that are not explicitly indicated in the musical score of a Mozart piano sonata. This research provides background information on the landscape of music cognition studies of the 1990s, indicating that the study of interaction between music and human communication should involve the study of physical or recorded performances rather than use of a score to quantify the stimuli and its effects. While the study lacks generalizability and employs a relatively small sample (N = 1), the hypotheses investigated extracted evidence of an expert musical performance delineated from the score through interpretation of notational information (e.g., dynamic choices between notes of different pitches), performance-specific sources of expression (e.g., instrument-related timing tendencies), general characteristics of performance expression (e.g., microtiming of note onset choices in dissonant vs. consonant chords), performer-specific expression (e.g., choices of timbre/resonance), and cultural/cognitive norms (e.g., prediction of tension-relaxation and melodic expectancy influencing dynamic and timing choices).

This case study posed novel hypotheses related to human musical expressive choice and opened many questions for further investigation into expressive choices made by performers and perceived (either consciously or unconsciously) by listeners. Through the lens of cognitive neuroscience, it is apt to ask what may be learned through investigating how humans process and transmit musical—or communicative—expression and how it differs from its source, whether a written score, an audio transmission, or other media source. The ways a performance differs from a musical score may uncover social and cultural expectations in emotionally expressive timing, communicative patterns in timbre, and decision in microtiming. Since music and language are both vehicles of expressive communication, there are crosscurrents in unwritten expressive choices occurring in written and spoken language as well, such as prosodic inflection in a reader, which correspond to musical expressive choice. While the differences between reading music and written words involve distinctive neural processes and cross-cultural considerations, this context can be leveraged to identify individual expressive choice (or the lack thereof) to be conceptualized as a form of cultural transmission, neurotype, or phenotype associated with different neurological conditions or health considerations. Generally, findings from music-language comparisons can shed light on the neural mechanisms underlying communicative expression and point to rehabilitative strategies for those facing communication-related developmental challenges.

A Theoretical Framework for Musical Expectation

Mental representations of predictability, expectation, and the element of surprise in musical experience have been notably investigated by Huron (2006), whose elegantly simple framework identifies different types of expectation and surprise in a musical context. His proposed concepts name four categories relating to musical expectation and surprise, which can be fluid and may shift in interpretation depending on the listener's exposure and experience with a musical work. Huron's four categories of expectation are: (1) Schematic: involving expectations emerging from an existing schema that a listener brings to their experience of a musical work; (2) Dynamic: involving expectations that are created within the context of the musical work; (3) Veridical: involving the use of musical forms or sounds that are unexpected and found in other domains; and (4) Conscious: involving verbalizable knowledge, such as knowing the song order of a favorite album.

Huron's recapitulative point that "the biological purpose of memory is not recall, but preparation" (Huron, 2006, p. 219) is an important reminder for scientific investigators to consider memory skills and memory processing differences when exploring concepts of event-attending, oscillatory rhythmic and meter entrainment, and patterns of social timing. Individual and clinical differences in attentional focus theoretically will lead to individual differences in memory. Populations with divergent attentional or memory experiences (e.g. post-traumatic stress disorder, attention-deficit hyperactivity disorder, autism spectrum disorder, Alzheimer's disease) may show identifiable behavioral or neural signatures of event preparation and surprise, perhaps further benefitting from tools leveraging musical expectation and surprise as metrics for identification and therapeutic use. While Huron's work is theoretically rich and poses several open-ended questions in the realm of memory, attending, expectation, and surprise, though herein we bracket the discussion of follow-up works to dive deeper into current neuroscientific explorations of these phenomena.

Initial Study and Replication Study: Exploring Rhythms in Perception

A study exploring human entrainment to acoustic rhythms reported that perceptual oscillation was effectively induced in listening participants for at least two cycles after the cessation of the rhythmic stimulus in which $N = 5$ and, in a follow-up experiment extending up to four cycles, $N = 3$ (Hickok et al., 2015). The findings of the study show positive indications of perceptual sensitivity oscillating after rhythmic auditory stimulation, though the analyses were limited by low statistical power. A multi-lab registered replication study published 10 years later with N = 60 did not find the same results and concluded that while neural entrainment remains a valuable concept, the behavioral signature reported in the original study might be weaker or less reliable than initially suggested (Henry et al., 2025). This pair of studies exemplifies the complexities of studying neural entrainment and the importance of transparency, replication, and clarity in identifying and reporting study limitations alongside results. While the replication study has significantly higher statistical power, a limitation of both studies is the lack of neural measurements in the experimental procedure. Future investigations exploring these hypotheses would benefit from implementing neural measurements in addition to replication of original behavioral measures, thereby illuminating the nuanced differences between the original and the replication study's findings.

Movement, Groove, and Syncopation Studies

When viewed through the lens of cognitive neuroscience, research on "groove," which has been defined in the psychological sciences as the pleasurable urge to move to music, can call for investigations of oscillatory attention (Spiech et al., 2024) and attempt to disentangle the degrees of rhythmic syncopation most related to body movement and pleasure in study participants (Witek et al., 2014). In clinical application, one study explored hypotheses related to the experience of groove in complex musical stimuli for populations with substance use disorders (Stupacher et al., 2025). Limitations of these studies include the use of simple drum stimuli, which may not be ecologically relevant to movement or dance-based musical activities, as well as terminological generalizations of rhythmic stimuli and reporting (e.g., using "syncopation" to describe rhythms that could be described more accurately using more nuanced language), hindering comprehension and translation of the work across different domains of academic research.

Future directions for studies in this realm include exploring tonal and melodic characteristics of music that may mediate or modulate a desire to move to music. Previously referenced scholarly work exploring anticipation and surprisal in musical experience provides ample hypotheses applicable to tonal expectation (Huron, 2006). As noted by Witek, moving to music inherently changes the aural experience of music. Further exploration of this phenomenon is a promising area of investigation that could have implications for applied work in brain-based processing and movement disorders.

A study by Duman et al. (2024) investigates the currently accepted, working definition of "groove," pointing out gaps in how participants interpret the term and how the term is applied to use in the psychological and brain sciences. Duman's study concluded that groove might be better identified as a "multidimensional participatory experience" (p. 93), marked not only by a pleasurable urge to move physically, but to mentally participate as well. The provides evidence that the experience of groove is a valid category for inclusion in the lexicon of the psychological sciences, though it still awaits a more encompassing definition and a set of sub-terminologies to adequately describe its multidimensionality as an experiential phenomenon.

Perception of Musical Meter

Three papers in this review relate to perception of musical meter. London (2004) provides a comprehensive theoretical background of the foundational psychological research supporting current explorations of time perception, dynamic attending, and entrainment. He proposes that meter and accent are entraining and attending processes for listening individuals, involving the development of a temporal schema based on past auditory events and prediction of future ones. Similarly, Povel and Essens (1985) characterize meter as hierarchical. Further, it has been found that metrical accents, while not present in stimuli, can be imposed by the listener (Brochard et al., 2003). These foundational concepts are interwoven throughout the more current research explored in this review, revealing a robust discussion on the role of meter in the perception of music and its relationship to temporal expectation.

Kalender et al. (2012) reports the results of an experimental study examining the influence of unfamiliar musical meter on a listener's ability to perceive a deviation from an established, repeated metrical meter. The participants in this study were stratified into groups described as "mono-musical" (familiarity with one musical tradition and meter, e.g., Western, Turkish, or Indian) and "bi-musical" (familiarity with two or more musical traditions and meters). The experimenters accounted for bilingualism and musical training in their analyses. Grouping the participants in this way introduces several lines of inquiry related to temporal experience in mono-musicality, bi-musicality and the perceptual narrowing of novel musical meter throughout an individual's developmental trajectory. The study reported that adults who listened exclusively to Western music detected changes in simple meter of Turkish music but not complex meter. Simultaneously, adults who listened occasionally to Indian music detected metrical changes in both simple and complex meter in Turkish music. The study is well-situated in cognitive neuroscience and music cognition literature, as it indicates that prior music experience significantly impacts the processing of meter cross-culturally. However, the results demand further illumination on the concept of bi-musicality. While the term implies a conceptual parallel to bilingualism, music and language involve distinctly different processes of exposure and absorption. Further investigations devoted to the nature of bi-musicality, and how it differs from bilingualism, could yield beneficial results for future work.

Povel and Essens' 1985 study investigates the ways that humans perceive and structure temporal patterns in rhythmic sequences. The cognitive framework proposed involves a listener's imposition of a mental "clock" that organizes time intervals into predictable patterns. Through three experiments, the authors explore how experiences of regularity, accents, and timing deviations affect rhythm perception and synchronization. The 1985 study left a definite legacy on subsequent studies of temporal and metric patterns, as it established how internalized time structures guide perception and reproduction of complex temporal patterns.

Dynamic Attending to Auditory Rhythms

A study by Jones et al. (2002) explores how rhythmic timing in auditory sequences influences attention and pitch perception. Across three experimental designs, the authors tested whether listeners' accuracy in judging pitch was affected by the timing of tones in a sequence. The results of the study support a model of dynamic attending, where attention aligns with predictable temporal structures. The study provides a robust illustration of the landscape of psychological literature in the realm of music cognition and psychological mechanisms of prediction and expectation at the time of publication. While the paper was published in 2002, scientific explorations continue to further expand on theories related to dynamic attending theory in the realm of auditory and cognitive neuroscience.

Wu et al. (2025) examine auditory-motor synchronization during musical experience, reporting a novel finding that unconscious eye blinks in EEG experiments are found to synchronize with a musical beat, controlling for tonal differences and tempo changes. Across multiple experiments, the strength of synchronization was found to be modulated by auditory attention. Stronger neural beat tracking resulted in more synchronization of blinks. These findings underscore the importance of developing experimental designs to identify the multimodal underpinnings of temporal tracking and auditory attention. New avenues for further refinement and exploration emerge, such as the examination of unconscious blinks as a biomarker for temporal attending in non-isochronous stimuli, as in naturalistic speech and speech-in-noise conditions.

Computational Representation of Musical Time

Desain and Honing's study (1989) represents a unique work in this review, as it centers on providing a novel, theoretical computational framework to represent the quantization of musical time. While this paper is primarily concerned with computational analyses, it is of additional interest to cognitive scientists working to disentangle musical time in perceptual experience related to application in user experience, psychological and cognitive science, and artificial intelligence research. The study proposed a framework of musical time operating on two separate time scales: beat-based (smaller) and expressive-based (larger), applying a connectionist approach consisting of interconnected elements within a complex network. At the time of publication, this method outperformed other approaches and represented a landmark contribution to the field.

The Problem of "Groove" in Music Science

The term "groove" appears frequently in music cognition literature, as explored in this review and beyond. Duman et al. (2024) report the results of an online study analyzing participants' understandings of the word "groove" throughout musical experience, i.e. what the associations the term "groove" evokes for listeners. Results overlap with the current definition of groove in the psychological sciences, and can be further expanded into territories related to solely mental experiences. Such findings could steer researchers towards considering Duman et al.'s proposed definition of a "multidimensional participatory experience" (p. 93) involving mental as well as physical engagement by the listener. New pathways emerge for investigations of attending, pleasure, and participatory engagement in musical experience. While the desire to move and participate in music is an intriguing concept to explore—in music cognition and cognitive neuroscience research—I propose that solely using the term "groove" to describe the phenomenon remains insufficient and overgeneralized.

Terminological Precision in Music Science Research

The limitations of language-based categorizations on human perception and experience are meticulously documented in seminal works throughout the field of psycholinguistics (e.g., Lakoff and Johnson, 1980). Since early uses of the concept of musical "groove," the term has been loosely defined, subjectively experienced, and globally popularized. While more research is needed, it is a valid concern that music cognition investigations attempting to contribute to an understanding of "groove" will face interpretive and translational challenges by relying on ambiguous terminology.

A large, multi-lab study deconstructing multiple aspects of "groove" into distinct, underlying constructs, such as rhythmic entrainment, motor affordance, affective engagement, and temporal attending, could more accurately describe the varied multidimensional experiences underlying the "pleasurable urge to move to music." Drawing on movement science frameworks like "affectively-charged motion states" (ACMS) and "psycho-physiological drive" (Stults-Kolehmainen et al., 2022; Stults-Kolehmainen, 2023) could inform components of this deconstruction and bridge terminology across relevant fields.

Toward Multidimensional, Predictive Temporal Hierarchies

Considering the perspective of an experienced musical performer accustomed to isochronous time and micro-timing of familiar meters, a worthwhile investigation for additional theoretical framing would explore the emergence of nonlinear, cross-hierarchical temporal expectations and tensions that occur simultaneously during music performance. Exploring these phenomena could further reveal more nuanced and complex hierarchical experiences of schematic, dynamic, and veridical expectation, in addition to surprisal experienced by those with primed memory and motor systems for such an experience. The phenomena could be further applied across variable domains such as cultural context, lifetime musical exposure, language experience, motor affordance, and affective states. Studying psychological musical phenomena while considering the impacts of individual differences using physiological neural measurements can yield more direct terms applicable to the experiences of these populations, perhaps guiding the definition of "groove" into new subcategories and conceptual domains, revealing the plurality of overarching, dynamic processes occurring in human musical experience.

Future Directions: Temporality, Neural Timing, and Human Communication

While this review has focused on temporal experience in music, the importance of temporality and neural timing in human language and communication is paramount. Musical timing is often beat-based (isochronous) and hierarchically categorized using simple frequency ratios, whereas speech timing contains hierarchical and non-isochronous rhythm and stress patterns, known as prosody. In both speech and music, the precisely timed coordination of sensorimotor gestures, facial expressions, head movements, and eye contact are crucial to conveying highly specific, meaningful messages. This poses the question: how do hierarchical rhythmic structures in music and language support multimodal communication and entrainment in social interactions? Further, what can this tell us about the neurobiological mechanisms underlying these processes?

The complex neurobiological processes underlying communicative timing enable elaborate and successful interpersonal information exchange—a vital skill for social cohesion and survival in all living species. While rhythmic processing in both music and language at least partially distinct, these processes are also known to share neural mechanisms and genetic architecture (Barchet et al., 2024; Alagöz et al., 2025). Recent studies exploring the multimodal underpinnings of language and music emphasize the need for ecologically valid study designs incorporating whole-body movement (e.g., co-speech gesture, beat gesture, posturing, and dance) and dyadic or group interactions (e.g., caregiver and child interactions, synchronization, speech-in-noise recognition) in temporal analyses. These investigations could contribute to a more comprehensive understanding of how afferent and efferent neural pathways support prediction and temporal attention, calling on multiple sensory systems to track, interpret, and express communicative messages (Hartmann et al., 2023; Momsen, 2024; Wu et al., 2025).

Prioritizing an investigation of temporally-driven, hierarchical frameworks across both music and language will be instrumental in disentangling the distinct and shared neural timing mechanisms across both modalities. This approach calls for (1) ecologically valid study design within naturalistic dyadic and group interactions, (2) the consideration of whole-body movement as central to temporal perception, and (3) multisensory integration.

Differences in temporal processing are implicated in a range of neurological conditions involving altered predictive coding, reduced multisensory integration, atypical memory functioning, and impaired motor abilities, all of which can cause difficulties in interpersonal communication. Across the human lifespan, a range of genetic and environmental influences can negatively affect the capacity for naturalistic communication and rhythmic processing, with downstream impacts at the level of the individual, family, community, and greater society. Contributing to a greater understanding of these temporal mechanisms across domains of language and music can inform future investigations and aid in the development of interventions for conditions involving impaired rhythm and communication skills.

Conclusion

This exploratory review, spanning fourteen works across forty years of music cognition research, has examined musical rhythm, meter, and temporal perception across a wide range of musical contexts and stimuli. While additional research is needed to cultivate understandings of cross-cultural and developmental musical phenomena, to establish greater terminological precision, and to explore neurophysiological measures that may support or refute aspects of currently adopted theoretical frameworks, the field of music cognition has made great strides in the last four decades. Pioneering studies have contributed to understandings that are deeply relevant to our collective understanding of perception, cognition, neuroscience, movement science, and human development.

To situate future music science research in an effective position for translatable, interdisciplinary application and cross-cultural collaboration, deconstructing ambiguous concepts and using precise language, (e.g., the concept of "groove") to develop future hypotheses will be paramount. Additionally, music cognition investigations should consider adopting: (1) ecologically valid designs incorporating naturalistic dyadic and group interactions, (2) frameworks positioning whole-body movement as central to temporal perception, and (3) active inclusion of multisensory integration. These considerations can position new hypotheses and investigations towards exploring a greater understanding of the multimodal, temporal underpinnings that support human connection, communication, and expression. They further allow us to uncover the distinct and shared neural mechanisms involved in both music and language processing, and to inform therapeutic and clinical applications.

Working to understand temporal hierarchies across the domains of music and language has great promise in contributing to an understanding that supports populations facing communication challenges, memory differences, movement disorders, and differences in multisensory integration. By leveraging the clear similarities and differences in music and language, researchers can move towards multidimensional frameworks supporting multimodal perception and action through hierarchical temporal relationships. This will advance a greater understanding of human communication and connection—skills essential for social cohesion, communicative agency, and survival.

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