Laboratorio de Inteligencia Artificial Aplicada

CONICET

# The role of the motor system in the processing of rhythmic complexity: a critical review


Cossavella, F.* , Miguel, M. A.° & Fernández Slezak, D.*

*Laboratorio de Inteligencia Artificial Aplicada, Departamento de Computación, Universidad de Buenos Aires, Buenos Aires, Argentina, Instituto de Investigación en Ciencias de la Computación (ICC), CONICET-Universidad de Buenos Aires, Buenos Aires, Argentina

°Department of Psychology, Neuroscience & Behaviour, McMaster University, Hamilton, ON, Canada

Contact: franciscocossavella@gmail.com


## Introduction

- The desire to move to music appears to be a human universal (1) and this behavioral response seems to be supported by a tight coupling of auditory and motor networks (2, 3).
- Even when no overt movement occurs, listening to music activates motor control regions in the brain (4).
- The phenomenon of motor system involvment in rhythm perception is explained by two predominant theories in terms of: dynamical system entrainment to musical periodicity (5) or motor system involvement in predictive processing (6). Both recognize the importance of rhythmic complexity.
- Predictive processing suggests that motor areas become more active during the perception of rhythms with medium complexity, generating a signal that engages the body in error minimization. In contrast, low or high complexity rhythms requiere less motor area engagement (7).
- Dynamical systems theories posit that auditory and motor oscillators synchronize to the beat in isochronous rhythms. In complex rhythms with high syncopation and low to no energy at the beat frequency, motor activity should remain consistent regardless of complexity, while auditory network closely tracks the frequencies present in the stimulus (8).

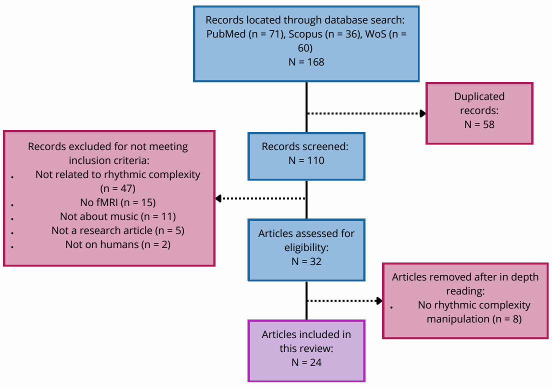
## Methods

We conducted an fMRI literature review to assess the relation between motor network activation and rhythmic complexity.

**Search string:** (rhythm* OR beat OR meter) AND (complex* OR syncopat*) AND (music*) AND (fMRI OR functional magnetic resonance imaging).

**Databases:** PubMed, Scopus, Web of Science (WoS).

**Inclusion criteria:** Peer reviewed fMRI research articles on humans manipulating musical rhythmic complexity with no time limit.




## Results

**Associations:** out of 24 studies, 13 (54.2%) reported increased motor area activation for more complex rhythms, with 8 of these comparisons involving medium complexity versus lower complexity. Six studies (25%) indicated either negative correlations or greater activation in motor areas for medium, not complex, rhythms. Three studies (12.5%) showed no significant complexity effect, 1 found a mixed effect, and 1 observed an inverted U-shaped relation between sensory-motor synchronization performance and motor area activation, with the highest correlation for medium complexity rhythms and smaller but significant correlations for low and high complexity rhythms.

**Complexity metrics:** 11 studies (45.8%) did not employ any, 5 (20.8%) used or referenced Povel & Essens for defining complexity, 3 (12.5%) applied the Pressing model, 2 (8.3%) used the C-score + Fitch and Rosenfeld's metric, and 2 (8.5%) used Pulse Clarity.

**Stimuli:** 4 studies used naturalistic stimuli, 7 used moderately ecological stimuli, and 13 employed stimuli with low ecological validity.

All studies were conducted by labs in the global north and predominantly on WEIRD populations (96%).

| | Methods | | | | | Results | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Article** | **Population** | **Task** | **Complexity metric** | **Relation** | **Stimuli (ecological validity)** | **Rest** | **Isochronous** | **Low complexity** | **Medium complexity** | **High complexity** | **Non-integer ratio** | **Random** |
| **Sakai et al., (1999)** | Non-musicians | Action | None | / | Single tones; non-repetitive; heard. | - | | | < PMC, cerebellum | | iso < PMC | |
| **Ullén, Forssberg & Ehrsson (2003)** | Non-musicians | Action | None | / | Single tones; repetitive; heard + performed. | | - | | < vPMC, dPMC, CMA, SMA, pre-SMA, cerebellum lobule IV | | | |
| **Lewis et al., (2004)** | Uncontroled | Action | None | / | Single tones; repetitive; heard. | - | | | | | SMA, pre-SMA, dPMC positive correlation with number of intervals | |
| **Chen, Penhune & Zatorre (2006)** | Non-musicians | Perception + action | Essens & Povel (1985) | / | Woodblock; non-repetitive; heard. | | | - | pre-SMA, dPMC, cerebellum lobule VI covariation with ITI standard deviation, same areas were found to be active during both passive and active conditions | | | |
| **Vuust et al., (2006)** | Musicians | Perception + action | None | / | Single song; repetitive; heard. | | | | - | < IFG | | |
| **Grahn & Brett (2007)** | Musicians and non-musicians | Perception + discrimination | Essens & Povel (1985) | \ | Single tones; repetitive; heard. | | | pre-SMA, SMA, caudado, pálido, putamen > | putamen > | | - | |
| **Thaut, Demartin, & Sanes (2008)** | Musicians | Perception + action | None | / | Single tones; repetitive; heard + performed. | - | | | < M1, S1, PMC, SMA, pre-SMA | | | |
| **Bengtsson, et al., (2008)** | Uncontroled | Perception | None | /, \ | Snare drum; repetitive; heard. | | IFG, pre-SMA > | | - | < cerebellum | | - |
| **Chen, Penhune & Zatorre (2008a)** | Musicians and non-musicians | Action | Essens & Povel (1985) | / | Woodblock; non-repetitive; heard. | | | - | pre-SMA, SMA, dPMC, vPMC, DLPFC, cerebellum lobule VI covariation with ITI standard deviation | | | |
| **Chen, Penhune & Zatorre (2008b)** | Non-musicians | Perception | Essens & Povel (1985). | / | Woodblock; non-repetitive; heard. | | | - | right SMA, left pre-SMA, right dPMC, left cerebellum lobule VI and right dlPFC covariation with ITI standard deviation | | | |
| **Berkowitz & Ansari (2008)** | Musicians | Action | None | / | Improvised piano; non-repetitive; performed. | - | | | | < dPMC, IFG | | |
| **Grahn & Rowe (2009)** | Musicians and non-musicians | Perception | Subjective validation | \ | Single tones; non-repetitive; heard. | | | | putamen > | | < no effect | |
| **Chapin et al., (2010)** | Musicians and non-musicians | Perception + WM | None | / | Single tones; repetitive; heard. | - | | | | < SMA, caudate | | |
| **Jungblut et al., 2012** | Non-musicians | Action | None | / | Human voice; repetitive; performed. | | | - | < IFG | | | |
| **Geiser, Notter & Gabrieli (2012)** | Uncontroled | Perception + distraction | None | \ | Single tones; repetitive; heard. | putamen > | | | | | | - |
| **Alluri et al., (2012)** | Musicians | Perception | Pulse Clarity | \ | Single song; repetitive; heard. | | | | SMA, putamen negative correlation with complexity | | | |
| **Kung et al., (2013)** | Musicians | Perception + attention | Essens & Povel (1985) | / | Woodblock; repetitive; heard. | | | | vlPFC positive correlation with complexity | | | |
| **Herdener et al., (2014)** | Musicians and non-musicians | Perception + distraction | None | / | Drumset; repetitive; heard. | | | | - | < IFG | | |
| **Tsatsishvili et al., (2014)** | Musicians | Perception | Pulse Clarity | \ | Single song; repetitive; heard. | | | | left SMA, IFG negative correlation with complexity | | | |
| **Vikene, Skeie, & Specht (2019a)** | PD and controls | Perception | Pressing + subjective validation | - | Bass drum + bass + piano chords; repetitive; heard. | | - | | | - | | |
| **Vikene, Skeie & Specht (2019b)** | PD and controls | Perception | Pressing + subjective validation | - | Bass drum + bass + piano chords; repetitive; heard. | | - | | | - | | |
| **Matthews et al., (2022)** | Musicians and non-musicians | Perception | C-score + Fitch & Rosenfeld | \ | Drumset + piano chords; repetitive; heard. | | | | putamen, caudate, pallidum, SMA, pre-SMA, bilateral dorsal PMC and right crus 1 in the cerebellum > | < no effect | | |
| **Færøvik, Specht & Vikene (2021)** | Musicians and non-musicians | Perception + attention | Pressing + subjective validation | - | Bass drum + bass + piano chords; repetitive; heard. | | - | | | - | | |
| **Siman-Tov et al., 2022** | Musicians and non-musicians | Perception | C-score + Fitch & Rosenfeld | ∩ | Drumset; repetitive; heard. | | - | < BA55b positive correlation with entropy, ENT standard deviation and LRV < | < BA55b positive correlation with entropy, ENT standard deviation and LRV > | > BA55b positive correlation with entropy, ENT standard deviation and LRV | | |

*CMA: cingualte motor area; d: dorsal; dl: dorsolateral; v: ventral; PD: Parkinsons Disease; PMC: pre-motor cortex; SMA: supplementary motor area; IFG: inferior frontal gyrus; M1: primary motor area; S1: primary sensory area; ITI: inter-tap interval; ENT: entropy; LRV: length of resultant vector.*
*Red color gradient indicates ecological validity from low (light) to high (dark).*
*Purple color gradient indicates degree of complexity.*
*- indicates contrast condition.*

## Discussion

Out of 110 reviewed articles, 24 reported findings ranging from non-existent to linear or inverted-U-shaped relations. When contrasts were organized by the level of complexity, we observed a pattern indicating that most medium complexity rhythms recruited motor areas significantly more when compared to lower and higher complexity rhythms, consistent with PP. However, underlying these findings, we encountered significant heterogeneity in the measurement and conceptualization of rhythmic complexity and an overall lack of theoretically driven hypothesis testing.

We conclude that, to make progress in elucidating the role of the motor system in processing rhythmic complexity, more agreement is needed regarding measures and concepts of complexity. Additionally, experiments should be designed to explicitly test theoretical predictions rather than rely on general associations. It's worth noting that all the research reviewed was conducted by teams from the global north, primarily on WEIRD populations (9), and only a small subset utilized ecologically valid stimuli. Furthermore, we believe the literature would greatly benefit from the use of more ecologically valid and multicultural stimuli, as well as the study of populations other than those from the global north. To this end, we are in the process of developing an ecologically and perceptually validated natural music dataset. Our aim is to use this dataset not only to assess the processing of rhythmic complexity across cultures but also to create a rhythmic complexity metric suitable for audio formats.

## References


1 - Singh, M., & Mehr, S. A. (2023). Universality, domain-specificity and development of psychological responses to music. Nature Reviews Psychology, 1-14.
2 - Kasdan, A. V., Burgess, A. N., Pizzagalli, F., Scartozzi, A., Chern, A., Kotz, S. A., ... & Gordon, R. L. (2022). Identifying a brain network for musical rhythm: A functional neuroimaging meta-analysis and systematic review. Neuroscience & Biobehavioral Reviews, 136, 104588.
3 - 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.
4 - Siman-Tov, T., Gordon, C. R., Avisdris, N., Shany, O., Lerner, A., Shuster, O., ... & Hendler, T. (2022). The rediscovered motor-related area 55b emerges as a core hub of music perception. Communications Biology, 5(1), 1104.
5 - Large, E. W., Roman, I., Kim, J. C., Cannon, J., Pazdera, J. K., Trainor, L. J., ... & Bose, A. (2023). Dynamic models for musical rhythm perception and coordination. Frontiers in Computational Neuroscience, 17, 1151895.
6 - Vuust, P., & Witek, M. A. (2014). Rhythmic complexity and predictive coding: a novel approach to modeling rhythm and meter perception in music. Frontiers in psychology, 5, 1111.
7 - Witek, M. A. (2017). Filling in: Syncopation, pleasure and distributed embodiment in groove. Music analysis, 36(1), 138-160.
8 - Large, E. W., Herrera, J. A., & Velasco, M. J. (2015). Neural networks for beat perception in musical rhythm. Frontiers in systems neuroscience, 9, 159.
9 - Henrich, J., Heine, S. J., & Norenzayan, A. (2010). The weirdest people in the world?. Behavioral and brain sciences, 33(2-3), 61-83.