Reference:

Alluri, V. & Toiviainen, P. (2023). The naturalistic paradigm: an approach to studying individual variability in neural underpinnings of music perception. Annals of the New York Academy of Sciences. https://doi.org/10.1111/nyas.15075

THE NATURALISTIC PARADIGM: AN APPROACH TO STUDYING INDIVIDUAL VARIABILITY IN NEURAL UNDERPINNINGS OF MUSIC PERCEPTION

[1]VINOO ALLURI and [2]PETRI TOIVIAINEN

Institutional Affiliations

[1]*Cognitive Science Lab, International Institute of Information Technology, Hyderabad, India*

[2]*Centre of Excellence in Music, Mind, Body and Brain, Department of Music, Art and Culture Studies, University of Jyväskylä, Finland*

Abstract

Music listening is a dynamic process that entails complex interactions between sensory, cognitive, and emotional processes. The naturalistic paradigm provides a means to investigate these processes in an ecologically valid manner by allowing experimental settings that mimic real-life musical experiences. In this paper, we highlight the importance of the naturalistic paradigm in studying dynamic music processing and discuss how it allows for investigating both the segregation and integration of brain processes using model-based and model-free methods. We further emphasize that studying individual difference-modulated music processing in this paradigm can provide insights into the mechanisms of brain plasticity, which can have implications for the development of interventions and therapies in a personalized way. Finally, despite the challenges that the naturalistic paradigm poses, we end with a discussion on future prospects of music and neuroscience research, especially with the continued development and refinement of naturalistic paradigms and the adoption of open science practices.

Corresponding author contact information:

Dr. Vinoo Alluri

Cognitive Science Lab, International Institute of Information Technology, Hyderabad-500032, India

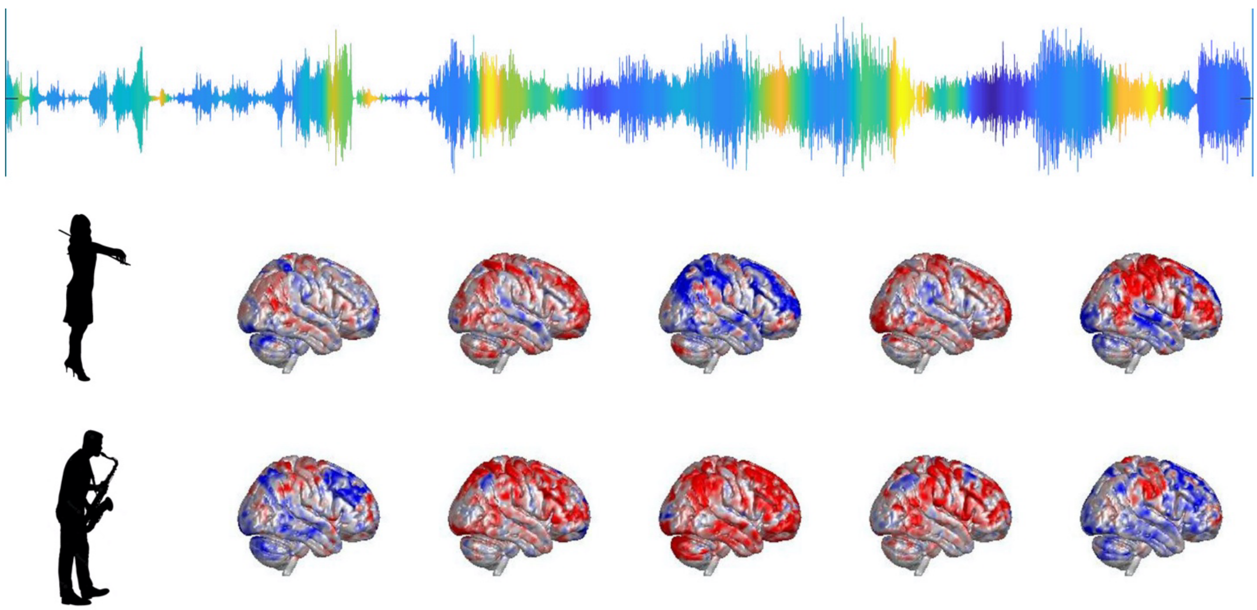
Email: vinoo.alluri@iiit.ac.in

Keywords

Naturalistic paradigm, individual differences, continuous music listening, predictive coding, dynamic processing

Graphical Abstract

We summarize the benefits of studying individual differences in dynamic neural processing of music using the naturalistic paradigm, which tries to emulate real-world music listening experiences. We highlight various model-based and model-free approaches used in fMRI studies to uncover individual differences in music processing. We discuss the limitations and future prospects of music and neuroscience research through development and refinement of naturalistic paradigms and the adoption of open science practices.



INTRODUCTION

Music is a unique and complex human experience, and studying individual differences in neural processing thereof can provide insights into the functioning and organization of the human brain. This knowledge can have wider implications for our understanding of other complex human abilities and a wide range of behaviors. Moreover, studying individual differences can provide insights into the mechanisms of brain plasticity, or the brain's ability to change and adapt in response to experience. This knowledge can have implications for the development of interventions and therapies in a personalized way that aim to promote brain plasticity. Indeed, musical stimuli might be good to unearth individual differences in brain processing in general, due to its complex and multimodal nature that engages multiple sensory and cognitive processes, and its universality and cultural ubiquity. Moreover, studies have reported that brain responses to naturalistic stimuli have been found to outperform those obtained during resting-state in studying various neural and behavioral traits[1–3].

The vast majority of the research on brain processing of music (be it about common patterns or individual differences) is set in a traditional controlled static paradigm, wherein the stimuli and presentation of them thereof do not typically emulate our everyday listening experiences. Listening to music is a dynamic process that involves continuous interplay between brain mechanisms involved in bottom-up encoding of sensory input and top-down predictive brain processes that operate at varying time scales. By making and updating predictions about the music we hear, our brain can extract meaning and pleasure from the soundscape and create a sense of coherence and flow in our experience of music. The predictive coding framework[4] characterizes these processes as hierarchical, in which we initially make first-order predictions based on incoming acoustic events, followed by second-order predictions that eventually elicit emotional responses related to our expectations of predictability[5]. Moreover, this continuous process of prediction and updating expectations happens at various levels of abstraction in the brain and most importantly is influenced by individual differences. Hence, to unearth these processes, it is crucial that we study music processing in a setting that affords examining dynamic brain states and their interaction over various temporal scales in addition to incorporating individual differences as an important modulator thereof.

From The Traditional Controlled Paradigm Towards The Dynamic Naturalistic Paradigm

The traditional controlled paradigm allows researchers to precisely manipulate, and control various aspects of the stimuli presented to participants, and examine potential causal relationships by observing changes in brain activity as a function of stimulus change. However, the controlled paradigm by design limits delving into the dynamic nature of music processing. Controlled paradigms can be artificial and may not capture the complexity of musical stimuli or the diversity of individual musical preferences and experiences. Moreover, they may not fully capture the temporal dynamics of music processing, as they often rely on snapshot measures of brain activity, which may limit the ability of researchers to understand the temporal unfolding of music processing and the coordination of different neural processes over time. In contrast, the dynamic naturalistic paradigm provides a means to investigate these complex dynamics while allowing for a more ecologically valid approach to studying music processing, including influences by a variety of factors, such as musical training, cultural background, and personal preferences. The seminal functional magnetic resonance imaging (fMRI) study in 2012[6] that employed the naturalistic paradigm in the field of cognitive neuroscience of music demonstrated for the first time the feasibility of using an entire piece of music and uncovering large-scale activation patterns associated with its features. A follow-up study in 2016[7] demonstrated the replicability of the findings, particularly of the processing mechanisms for low-level musical features thereby supporting the use of the naturalistic paradigm as a reliable approach to studying dynamic music processing.

MODEL-BASED AND MODEL-FREE APPROACHES TO INVESTIGATING BRAIN RESPONSES

The dynamic naturalistic paradigm offers an approach to studying brain processes in terms of both segregation (processing information as separate and distinct components) and integration (combining information from multiple sources to form a coherent whole), utilizing a range of methods that can be broadly categorized as model-based or model-free. Model-based methods use external regressors to model brain responses, with typical such regressors being time-varying musical features extracted through methods of Music Information Retrieval (MIR) or dynamic ratings of a perceptual attribute of music. Model-free approaches rely entirely on the analysis of brain responses with no reference to acoustic or perceptual features of the stimulus.

The model-based and model-free approaches, along with their basic assumptions, approaches and methods, are summarized in Table 1.

	Assumptions	Methods	
		segregation	integration
Model-based	External regressor	SPM[8]	PPI[9]
Model-free	no external regressor	ISC[6], ISPS[12]	PCA[11], ICA[11,14], graph-based methods[10,13]

Table 1. Model-based and model-free approaches in naturalistic music neuroscience. SPM = statistical parametric mapping; PPI = psychophysiological interaction analysis; ISC = inter-subject correlation; ISPS = inter-subject phase synchrony; PCA = principal components analysis; ICA = independent component analysis.

In what follows, we provide examples of our previous fMRI studies on individual differences in neural processing of music, in particular, related to musical training, using both model-based and model-free paradigms.

Using a model-based naturalistic paradigm with continuous acoustic features as regressors, Niranjan et al.[8] found that musicians demonstrated greater involvement of limbic and reward regions but failed to exhibit large regions of consistent correlation patterns for high-level features, while non-musicians showed broader regions of correlations, implying greater similarities in bottom-up sensory processing. In a model-based functional connectivity study using Psychophysical Interaction Analysis (PPI), Burunat et al.[9] found that musical training is associated with increased predictability-driven coupling between the cerebellum and hippocampus during music listening, suggesting that predictive listening accuracy is improved by musical training.

Using a model-free graph-theoretical approach, Alluri et al.[10] investigated the effect of musical training on functional connectivity during music listening and found that musicians showed enhanced integration of motor and auditory information, suggesting increased action-based processing. In a supervised machine learning study, Niranjan et al.[11] used ICA with sliding time window correlations to classify participants according to their musical training based on their dynamic functional connectivity patterns. In another machine learning study, Gandhi et al.[12] found that using dynamic functional connectivity patterns as features outperformed by a significant margin their static counterparts in identifying individuals. Using eigenvector centrality mapping, Moorthigari et al.[13] found that cognitive empathy was associated with higher centrality in sensorimotor regions responsible for motor mimicry, while affective empathy was associated with higher centrality in regions related to auditory affect processing. Finally, combining model-free and model-based paradigms, Burunat et al.[14] used region-based ICA along with a computationally extracted beat salience regressor to investigate the coupling of action-perception brain networks during musical pulse processing. They found that the networks' activity was better predicted by beat salience in non-musicians, suggesting that their beat processing was more stimulus-driven than with musicians.

An important caveat is that all the above studies were performed on the same dataset[15]. While this may be seen as a potential limitation to the conclusions one can draw, it is however noteworthy that employing model-based and model-free approaches allows us to reach congruent conclusions about musical expertise-modulated music processing. For instance, in several of the aforementioned studies musicians demonstrated less consistencies in DMN-related regions when compared to non-musicians. On the other hand, somatomotor regions were consistently found to play a key role in organizing brain connectivity in musicians while the auditory areas played a greater role in music processing in non-musicians. In other words, these studies suggest that musicians employ an action-oriented predictive processing model (AOPP) that tries to minimize the prediction error by actively engaging the motor system internally to generate the motor commands needed to fulfill the predictions, while non-musicians employ a perception-based approach which attempts to match incoming sensory information based on modification of top-down predictions. Such conclusions in light of individual differences in music processing can only be reliably drawn if researchers apply multiple methods on a single dataset and find consistent results.

DISCUSSION

FMRI studies that utilize the dynamic naturalistic paradigm have been on the rise especially in the visual modality over the past decade[16-19]. There are reasons to hence expect the same in the auditory modality owing to the advantages and promises it demonstrates. First, naturalistic stimuli allow for the study of brain processes that occur organically, as they closely resemble the experiences that people have in the real world. Second, naturalistic stimuli can better capture the variability in responses between individuals, as they are not constrained by a rigid experimental design. This in conjunction with acquiring multimodal information, such as EEG/MEG data or continuous behavioral ratings, permits investigating dynamic brain states. Third, using naturalistic stimuli allows us to investigate complex interactions between sensory, cognitive, and emotional processes that occur during music listening and can lead to novel insights into the neural mechanisms of music processing that may be missed in more controlled paradigms. And most importantly, the dynamic naturalistic paradigm allows for the use of a range of methods, including model-based and model-free approaches, which can provide complementary information about brain processes. Finally, owing to the complexity of the distributed activation patterns emerging as a result of several cognitive processes that come into play while processing music, advanced techniques such as multi-voxel pattern analysis (MVPA) and representational similarity analysis (RSA) would be apt choices. Using MVPA and RSA to analyze brain responses to naturalistic stimuli offers several advantages over traditional univariate analyses, including the ability to capture more complex neural patterns, greater discriminative power, and the ability to test hypotheses about neural representations.

Challenges of the naturalistic paradigm

The dynamic naturalistic paradigm comes with its own set of challenges. Naturalistic stimuli are often complex and high-dimensional, and the musical features can exhibit multicollinearity leading to stimulus-dependent confounds. This may render it difficult to unravel the associations between brain responses and individual musical features. One way to potentially mitigate this is to systematically manipulate specific musical features of naturalistic stimuli in a controlled manner to investigate their effects on brain activity and behavior. Additionally, the researcher has to be able to identify features that are important for evoking brain activity or are associated with certain distributed patterns of brain activity, and has to model them appropriately, especially in a manner that has perceptual relevance. However, employing a multimodal approach in the naturalistic paradigm of including complementary information from behavioral responses, and simultaneous EEG would lead to improved spatial and temporal resolution, cross-validation of results, leading to a more nuanced understanding of cognitive processes, and improved statistical power. Also, the longer durations of temporal data that the naturalistic paradigm affords as opposed to the controlled paradigm has the added advantage of improved statistical power.

From the Replicability crisis towards "multiverse analysis" of complex data

Recently, concerns about the reliability and robustness of fMRI findings, as well as the high rate of false positives reported in some studies have given rise to a replicability crisis. In the notable work by Botvinik-Nezer et al.[20], the authors report substantial variability in the results reported by multiple research groups that analyzed limited hypotheses of a single fMRI dataset with varying analyses pipelines. They highlight the need for *multiverse analysis*, an approach that involves systematically exploring different analytical choices or modeling decisions that can be made in the analysis of complex data, akin to those obtained using the naturalistic paradigm, in conjunction with meta-analyses is proposed as a promising solution and future direction in fMRI. This is similar to what we have demonstrated in this perspective paper: analyzing a dataset using multiple methods allowed us to identify coherent and consistent findings and consequently allow us to contribute to the field of music and neuroscience in an increasingly reliable and valid way. Finally, with the push in the neuroscience community towards using open science practices, including data sharing (e.g. openfMRI[21]), analysis scripts and software[22], results, study protocols and analysis plans, and awareness of the importance of *multiverse analysis*, the future for the naturalistic paradigm is promising.

CONCLUSION

The naturalistic paradigm is paving way to understanding how the brain processes complex real-world stimuli. It affords a space that allows for the integration of a range of assessment methods in tandem, such as physiological and behavioral measures, to provide a more comprehensive understanding of the brain mechanisms underlying musical perception and cognition and has the potential to reveal how these mechanisms vary across different musical contexts and individuals. Furthermore, this approach has the potential to revolutionize the field of neuroimaging and provide new avenues for understanding brain function and developing interventions for neurological and psychiatric disorders, be it in the context of music or otherwise.

AUTHOR CONTRIBUTIONS

VA and PT contributed equally.

ACKNOWLEDGMENTS

This work was supported by the Academy of Finland (project 346210).

COMPETING INTERESTS

We declare no competing interests.

REFERENCES

1. Gal, S., Coldham, Y., Tik, N., *et al.* 2022. Act natural: Functional connectivity from naturalistic stimuli fMRI outperforms resting-state in predicting brain activity. *NeuroImage* 258: 119359.
2. Finn, E. S., Glerean, E., Khojandi, A. Y., *et al.* 2020. Idiosynchrony: From shared responses to individual differences during naturalistic neuroimaging. *NeuroImage* 215: 116828.
3. Vanderwal, T., Eilbott, J., & Castellanos, F.X.. 2019. Movies in the magnet: Naturalistic paradigms in developmental functional neuroimaging. *Dev. Cogn. Neurosci.* 36: 100600.
4. Friston, K., & Kiebel, S. (2009). Predictive coding under the free-energy principle. *Philosophical transactions of the Royal Society B: Biological sciences*, *364*(1521), 1211-1221.
5. Koelsch, S., Vuust, P., & Friston, K. (2019). Predictive processes and the peculiar case of music. *Trends in cognitive sciences*, *23*(1), 63-77.
6. Alluri, V., Toiviainen, P., Jääskeläinen, I. P., Glerean, E., Sams, M., & Brattico, E. (2012). Large-scale brain networks emerge from dynamic processing of musical timbre, key and rhythm. *Neuroimage*, *59*(4), 3677-3689.
7. Burunat, I., Toiviainen, P., Alluri, V., Bogert, B., Ristaniemi, T., Sams, M., & Brattico, E. (2016). The reliability of continuous brain responses during naturalistic listening to music. *NeuroImage*, *124*, 224-231.
8. Niranjan, D., Burunat, I., Toiviainen, P., *et al.* 2019. Influence of Musical Expertise on the processing of Musical Features in a Naturalistic Setting. In *2019 Conference on Cognitive Computational Neuroscience* Berlin, Germany: Cognitive Computational Neuroscience.
9. Burunat I., Brattico, E., Hartmann, M., *et al.* 2018. Musical training predicts cerebello-hippocampal coupling during music listening. *Psychomusicology Music Mind Brain* 28: 152–163.

10. Alluri V., Toiviainen, P., Burunat, I., *et al.* 2017. Connectivity patterns during music listening: Evidence for action-based processing in musicians. *Hum. Brain Mapp.* 38: 2955–2970.
11. Niranjan, D., Toiviainen, P., Brattico, E., *et al.* 2019. Dynamic Functional Connectivity in the Musical Brain. In *Brain Informatics* Liang, P., Goe,l V., & Shan, C., Eds. 82–91. Cham: Springer International Publishing.
12. Gandhi, R., Garimella, A., Toiviainen, P., *et al.* 2020. Dynamic Functional Connectivity Captures Individuals' Unique Brain Signatures. In *Brain Informatics* Mahmud, M., Vassanelli, S., Kaiser, M.S., et al., Eds. 97–106. Cham: Springer International Publishing.
13. Moorthigari, V., Carlson, E., Toiviainen, P., *et al.* 2020. Differential Effects of Trait Empathy on Functional Network Centrality. In *Brain Informatics* Mahmud, M., Vassanelli, S., Kaiser, M.S., et al., Eds. 107–117. Cham: Springer International Publishing.
14. Burunat, I., Tsatsishvili, V., Brattico, E., Toiviainen. P. (2017) Coupling of Action-Perception Brain Networks during Musical Pulse Processing: Evidence from Region-of-Interest-Based Independent Component Analysis. Front Hum Neurosci. 2017 May 9;11:230. doi: 10.3389/fnhum.2017.00230. PMID: 28536514; PMCID: PMC5422442. 11:.
15. Burunat, I., Brattico, E., Puoliväli, T., Ristaniemi, T., Sams, M., & Toiviainen, P. (2015). Action in perception: prominent visuo-motor functional symmetry in musicians during music listening. *PloS one*, *10*(9), e0138238.
16. Zhang, Q., Li, B., Jin, S., Liu, W., Liu, J., Xie, S., ... & Yang, Z. (2022). Comparing the Effectiveness of Brain Structural Imaging, Resting-state fMRI, and Naturalistic fMRI in Recognizing Social Anxiety Disorder in Children and Adolescents. *Psychiatry Research: Neuroimaging*, *323*, 111485.
17. Zhang, X., Liu, J., Yang, Y., Zhao, S., Guo, L., Han, J., & Hu, X. (2022). Test–retest reliability of dynamic functional connectivity in naturalistic paradigm functional magnetic resonance imaging. *Human brain mapping*, *43*(4), 1463-1476.
18. Kringelbach, M. L., Perl, Y. S., Tagliazucchi, E., & Deco, G. (2023). Toward naturalistic neuroscience: Mechanisms underlying the flattening of brain hierarchy in movie-watching compared to rest and task. *Science Advances*, *9*(2), eade6049.
19. Gao, J., Li, C., He, Z., Wei, Y., Guo, L., Han, J., ... & Zhang, T. (2022, March). Prediction of cognitive scores by movie-watching fmri connectivity and eye

movement via spectral graph convolutions. In *2022 IEEE 19th International Symposium on Biomedical Imaging (ISBI)* (pp. 1-5). IEEE.
20. Botvinik-Nezer, R., Holzmeister, F., Camerer, C. F., Dreber, A., Huber, J., Johannesson, M., ... & Rieck, J. R. (2020). Variability in the analysis of a single neuroimaging dataset by many teams. *Nature*, *582*(7810), 84-88.
21. openfMRI, http://openfmri.org/
22. Lartillot, O., & Toiviainen, P. (2007). A Matlab toolbox for musical feature extraction from audio.. Proc of the 10th Int Conference on Digital Audio Effects DAFx07, 1–8. Available at http://bit.ly/mirtoolbox

		Segregation	Integration	Model-based	Model-free	Invariance	Variance
A	Alluri et al. 2012	x		x	x	x	
B	Alluri et al. 2013	x		x		x	
C	Toiviainen et al. 2014	x		x		x	
D	Burunat et al. 2014	x		x		x	
E	Burunat et al. 2015		x		x		x
F	Alluri et al. 2015		x		x		x
G	Burunat et al. 2016	x		x		x	
H	Alluri et al. 2017		x		x		x
I	Burunat et al. 2017		x	x	x		x
J	Saari et al. 2018	x		x			x
K	Hoefle et al. 2018	x		x		x	
L	Tsatsishvili et a. 2018	x		x		x	
M	Niranjan et al. 2019a	x		x		x	
N	Niranjan et al. 2019b		x		x		x
O	Toiviainen et al. 2020		x	x		x	
P	Gandhi et al. 2020		x		x		x
Q	Moorthigari et al. 2020		x		x		x