JSM (15) (1)

JURNAL SENI MUSIK

https://journal.unnes.ac.id/journals/jsm/index

Effects of Personalized Prosodic Sentences and Isomorphic Melodies on Children's Brain Activity

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Article Info

Received: May, 2026

Approved: June, 2026

Published: June, 2026

Keywords:

Prosody, isomorphic melody, brain activity, music-speech overlap

Abstract

This study examined the effects of personalized speech and melodic stimuli on brain activity in 19 children using a within-subject quasi-experimental design and single-channel EEG. Participants listened to prosodic sentences and isomorphic melodies mimicking prosodic features. Gamma, alpha, and theta activity were compared across conditions. No significant differences were found in alpha ($Z = -0.322$, $p = 0.748$) or theta ($Z = -1.328$, $p = 0.184$), while gamma activity was significantly lower during melody than prosody ($Z = -2.133$, $p = 0.033$, $r = 0.49$). The findings suggest partially overlapping neural processing of speech and music, with higher gamma activity during prosody indicating greater demands for integrating acoustic and linguistic information.

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ISSN 2503-2860

INTRODUCTION

In recent decades, music has received increasing attention because of its benefits, including its potential application in the therapeutic field. This is possible because musical activities that are designed to meet the participants' needs can improve various emotional aspects, such as emotional well-being (Wilms et al., 2020), self-esteem (Chang et al., 2018), and even social interaction and friendship (Oktadus & Yaqin, 2017). The growing number of studies on music and emotion shows that music has important therapeutic potential because of its significant influence on emotional processes. One area in music therapy that still offers opportunities for further exploration is music therapy for individuals with language disorders, such as developmental language disorder (DLD), aphasia, and language disorders caused by traumatic brain injury. These disorders are often associated with damage or abnormalities in specific brain regions responsible for language processing (Dessy, 2018). This therapeutic potential is supported by two important facts. First, the brain has neuroplasticity, which provides opportunities for functional recovery. Second, music and language processing share many common neural domains in the brain (Miller, 2025).

Language competence is an essential aspect of human social life. This is because language, like music, is one of the most distinctive human abilities and is not found in other living beings. The loss or decline of language competence can reduce a person's quality of life because human life is closely connected to this ability. Humans use language to communicate, express emotions, and share ideas. The ability to think abstractly and logically, which is important for identifying and solving problems, also depends greatly on language competence (Borghi, 2020; Williams et al., 2017). In addition, many studies have reported that different types of language disorders can negatively affect various aspects of human life, including communication skills, work performance, and emotional well-being (Beitchman & Brownlie, 2005; Whitehouse et al., 2009; Wilmot et al., 2024).

However, the therapeutic application of music for individuals with language disorders is still far from effective. According to previous reports, the success rate of music-based interventions is only about 20–40% (Elbe, 2024; Suri, 2022). This indicates that many specific aspects are still not well understood before this type of therapy can be applied effectively. As a result, music-based interventions are still mainly limited to experimental settings and are not yet widely available as part of general healthcare services that can be accessed by the public. To create greater therapeutic opportunities, knowledge in this research area needs to continue developing until it reaches a stage where the accumulated evidence can be integrated into more effective and well-established intervention approaches.

One issue that may improve this understanding is identifying which elements of music are processed in parallel with language in the brain. This knowledge may provide new opportunities for therapeutic applications through the mechanism of neuroplasticity. Therefore, this study aims to extend previous research by examining the extent to which listening to music and language (speech) share common neural processing in the brain. This is important for identifying which musical elements are processed most similarly to language and may therefore have greater potential for therapeutic use.

Pitch and rhythm are two musical elements that have a close relationship with prosody (intonation) in spoken language. Many previous studies have shown that the processing of pitch in music is closely related to the processing of intonation in prosodic speech. For example, Bedoya et al. (2021) found similar patterns of arousal and valence in participants when they listened to both speech and instrumental sounds. Their findings suggest that emotional processing in music also relies on mechanisms used to process vocal emotions in communication through acoustic features that are shared by both types of stimuli. This finding was further supported by Wang et al. (2023), who compared these processes in individuals with autism spectrum disorder (ASD) and non-ASD participants. They found greater variability in the ASD group, although the overall pattern of mental representation was similar to that of the non-ASD group. These results suggest that individuals with ASD show greater heterogeneity in the processing of emotional information.

Music and language processing overlap because they share the processing of common acoustic features, especially pitch and changes in vocal intonation in prosodic speech. These shared processes mainly involve the right hemisphere, particularly the superior temporal gyrus (STG) and the inferior frontal gyrus (IFG) (Sammler et al., 2015; Zatorre & Gandour, 2008). However, although music and prosodic speech show overlapping neural processing, they are processed in different brain modules. In other words, the overlap occurs because music and language share neural resources for processing auditory stimuli rather than using exactly the same neural networks (Patel, 2011). Therefore, the overlap does not indicate complete similarity in the neural systems involved. This can be seen in the study by Lacroix et al. (2015), which found differences in the activation of temporal brain networks during music and language processing. Similar evidence was reported by DePriest et al. (2017), who demonstrated a dissociation between music and language processing. For example, in individuals with autism spectrum disorder (ASD), abnormalities in brain networks may affect language processing while leaving music processing relatively preserved. Likewise, the processing of musical pitch is not disrupted by damage to brain regions that are responsible for language syntax.

Specific differences in the processing of temporal structure across brain regions may provide further evidence for the existence of both domain-general and domain-specific neural resources. For example, damage to Broca's area can impair syntactic integration, while simple temporal processing may still be carried out by the superior temporal gyrus (STG). This suggests that the STG plays a more domain-general role in temporal processing, whereas more complex and language-specific syntactic processing requires specialized brain regions, such as Broca's area.

Although both music and speech are processed as temporal auditory stimuli, this temporal processing begins in the domain-general function of the superior temporal gyrus (STG), particularly in processing the rhythmic consistency of auditory signals (van Atteveldt et al., 2015). The overlap in this region is mainly limited to the temporal and sequential detection of basic units, such as words or musical notes, and does not extend to the processing of grammar and semantic meaning that is required for speech. However, this stage of processing is involved in emotion recognition in both music and speech. For example, Pinheiro et al. (2015) found that musicians showed more efficient early auditory processing (P50 and N100) and higher accuracy in recognizing angry prosody in sentences without semantic content (PPC). These findings support the hypothesis that musical expertise enhances sensitivity to acoustic cues in vocal communication. Similarly, Zioga et al. (2016) investigated the interaction between melodic expectation in music and prosody in language, as well as the influence of musical training on pitch processing in both domains. They found that musicians were faster and more accurate in identifying questions and statements and also responded more quickly when expectations were violated in both music and language.

Most studies on the overlap between music and prosody have focused on adults. In addition, emotional processing has been identified as the most prominent aspect shared by both domains, making emotion a central component of their overlapping neural processing. In relation to therapeutic applications, the central role of emotion is consistent with a more personalized approach that considers the perspectives and affective needs of individuals to support personal growth, self-actualization, and emotional well-being (McLeod, 2023). Several event-related potential (ERP) studies, including the work of Tacikowski et al. (2014), have shown that using stimuli that are personally relevant and familiar to participants, such as their own name or the name of a close family member, produces stronger preferential responses and influences subsequent information processing. A meta-analysis also found that voice familiarity affects which neural processing pathways become more active during auditory processing (Sun et al., 2023).

Although previous studies have shown that voices and words with personal significance produce different effects on word processing, this factor has received limited attention in studies investigating the overlap between music and language processing. Voices and words that are personally relevant to the participant can influence both implicit and explicit word processing. Therefore, emphasizing personal relevance in stimulus design may provide new insights into the overlap between the processing of prosodic speech and melody. However, only a few experimental studies have used a personalized approach, such as prosodic speech and melodic stimuli that include the participant's name and activities that are familiar or relevant to them, especially in young children. Therefore, the present study aims to specifically examine the overlap in brain responses to music and language (speech) stimuli that contain personally relevant or familiar information.

Among the brain oscillations that can be recorded using EEG, several frequency bands have been identified as important indicators of cognitive processing during the presentation of both prosodic speech and melodic stimuli. In his review article, Klimesch (1999) summarized evidence from previous studies showing that EEG oscillations, particularly the alpha and theta bands, reflect cognitive processes such as attention, semantic memory, and the encoding of new information. The patterns of these oscillations vary depending on the type of memory task being performed. Klimesch referred to two major memory systems. The first is the Working Memory System (WMS), which is involved in encoding new episodic information. The second is the Long-Term Memory System (LTMS), which is responsible for storing and retrieving semantic information. Alpha and theta oscillations are assumed to have different functions. Alpha activity is mainly associated with thalamo-cortical processes, especially semantic memory and attention, whereas theta activity is associated with hippocampo-cortical loops, particularly during the encoding of new information and episodic memory.

The conceptual framework proposed by Klimesch (1999) explains the mechanisms of brain oscillations during cognitive processing. Large-scale alpha synchronization, or upper alpha (type 1), reflects a resting state, whereas alpha desynchronization, or lower alpha (type 2), reflects the activation of specific cortical networks during cognitive processing. In contrast, regular theta synchronization (type 2) is associated with information encoding through hippocampo-cortical loops, while irregular theta synchronization (type 1) is associated with reduced cognitive performance. These findings suggest that alpha and theta oscillations can serve as biomarkers of cognitive performance. As cognitive demands increase, mean alpha power tends to decrease. In contrast, as the brain processes more new and complex information, mean theta power tends to increase. Gamma oscillations, on the other hand, are involved in feature binding and cognitive integration in the cortex (Buzsáki, 2006). The interaction of these oscillations enables the brain to reconstruct the sequence of events (Nyhus & Curran, 2010).

Previous studies have shown that language and music processing share common neural resources in the brain. This overlap is especially found in brain regions involved in processing auditory and temporal features, such as pitch, tempo, sound intensity, and even simple temporal structures that are present in both music and language. However, speech processing appears to involve more complex neural processes, particularly those related to grammatical integration and semantic interpretation, which are reflected in theta, alpha, and gamma oscillations. Based on previous findings, this study proposes the following hypothesis: (H1): Alpha oscillatory activity during the processing of prosodic speech will be lower, whereas theta activity will be higher, than during the processing of melodic stimuli.

METHOD

This study employed a within-subject quasi-experimental design based on the framework proposed by Shadish et al. (2002). In this design, each participant served as his or her own control, allowing brain responses to be compared across different stimulus conditions. The study aimed to compare children's brain activity during exposure to prosodic speech (intonation) and isomorphic melody (an instrumental melody that imitates the prosodic pattern without words). Prosodic speech consisting of a play invitation that included the participant's name (Condition 1) and an isomorphic melody (Condition 2) were treated as the independent variables. Brain activity, as represented by EEG brain wave oscillations, served as the dependent variable. Each participant was exposed to both conditions: (1) listening to a prosodic play invitation addressed by the participant's name, and (2) listening to an instrumental melody that matched the pitch intervals and rhythmic pattern of the prosodic speech (isomorphic melody).

Population

Data were collected at Kanisius Kembaran Elementary School, Jl. Kembaran No. 89, Tamantirto, Kasihan, Bantul, Special Region of Yogyakarta, Indonesia, with 19 children participating in the study (approximately 9–10 years old). Before data collection, permission was obtained from the school, and written informed consent was obtained from the parents or legal guardians of all participants. The parents or guardians were also informed about the purpose of the study and the data collection procedures and were assured that participation involved no known risks. Children whose parents agreed to participate (N = 19) were then registered using their full names and preferred first names (consisting of two to three syllables). These preferred names were later used in the experimental stimuli. The participants were also informed about the schedule for the data collection sessions.

Stimulus Design

The stimuli were custom-designed for each participant by adjusting the participant's preferred first name, gender (a boy's voice for male participants and a girl's voice for female participants), and the number of syllables in the participant's name, which determined the rhythmic pattern of the melodic stimulus. The prosodic speech stimuli were recorded by one boy and one girl who were not included in the study sample but were within the same age range as the participants. Both voice actors had received vocal training. Each voice actor recorded a play invitation that included the preferred first name of every participant.

For the isomorphic melody stimuli, a violin timbre was selected based on previous studies suggesting that the violin resembles human vocal expression because it has comparable expressive characteristics, such as vibrato, dynamics, and controllable note duration. The isomorphic melodies were adapted according to the number of syllables in each participant's preferred first name (two or three syllables). Each syllable was matched to the same pitch interval and rhythmic pattern used in the corresponding prosodic speech stimulus (Condition 1: play invitation with prosody). All voice and instrumental recordings were conducted in a soundproof recording studio.

Procedure

Each participant was presented with both stimulus conditions, and the order of presentation was randomized across participants. The prosodic speech stimulus consisted of a play invitation that addressed the participant by his or her own name, whereas the melodic stimulus consisted of an instrumental melody with a rhythmic pattern matched to the number of syllables in the participant's name (two or three syllables). The audio stimuli were played from a laptop connected to a pair of true wireless stereo (TWS) earphones worn by the participants during EEG recording. Brain activity was recorded using a single-channel MindWave EEG device. Each stimulus condition was presented alternately, with a 30-second interval between conditions before the next stimulus was delivered.

Data Analysis

The EEG data were analyzed using IBM SPSS Statistics 26. Normality tests were first conducted, and because the data did not meet the assumption of normality, differences between the two stimulus conditions were examined using the Wilcoxon signed-rank test. The statistical results were then interpreted and discussed in relation to previous studies on similar topics. Not all EEG frequency bands were included in the analysis. The selected frequency bands were determined based on previous literature showing that only certain oscillations are informative for examining the overlap between music and language processing. Therefore, the analyses focused on the alpha, theta, and gamma frequency bands, as these oscillations are considered to reflect the extent to which speech and instrumental music share common neural processing resources.

RESULT AND DISCUSSION

To compare the characteristics of brain wave activation between the two stimulus conditions, the mean voltage of each EEG frequency band was calculated across the time frame of each stimulus before statistical analysis. The normality test showed that not all EEG data were normally distributed ($p < .05$). Because some of the data did not meet the assumption of normality based on the Shapiro–Wilk test, differences between the two stimulus conditions were analyzed using the non-parametric Wilcoxon signed-rank test.).

Table 1. Comparison of EEG Power Between the Prosody and Melody Conditions (Wilcoxon Signed-Rank Test)

Variable	N	Prosody, Mean (SD)	Melody, Mean (SD)	Z	p (*2-tailed*)	Effect Size (r)	Direction of Effect
Alpha	19	0.00620 (0.00194)	0.00591 (0.00173)	-0.322	0.748	0.07	Mixed (↓11, ↑8)
Gamma	19	0.00168 (0.00055)	0.00138 (0.00064)	-2.133	0.033*	0.49	Decrease (↓15, ↑4)
Theta	19	0.02507 (0.01004)	0.02098 (0.00598)	-1.328	0.184	0.30	Decrease (↓12, ↑7)

The Wilcoxon signed-rank test revealed a significant reduction in gamma activity in the melody condition compared with the prosody condition (Z = -2.133, p = .033, r = .49). Mean gamma power was higher in the prosody condition (M = 0.00168, SD = 0.00055) than in the melody condition (M = 0.00138, SD = 0.00064). In contrast, no significant differences were found for alpha (Z = -0.322, p = .748, r = .07) or theta activity (Z = -1.328, p = .184, r = .30). For the alpha band, mean power was similar between the prosody condition (M = 0.00620, SD = 0.00194) and the melody condition (M = 0.00591, SD = 0.00173). Likewise, mean theta power was higher in the prosody condition (M = 0.02507, SD = 0.01004) than in the melody condition (M = 0.02098, SD = 0.00598), although this difference was not statistically significant.

These findings support previous studies suggesting that music and language share overlapping neural processing, but the overlap is not entirely symmetrical. Instead, only some aspects of music and language processing appear to rely on common neural resources. The comparison between the prosody and melody conditions across the three EEG frequency bands supports this interpretation. No significant differences were observed in the alpha and theta bands, whereas a significant difference was found in the gamma band.

Alpha Oscillations in the Processing of Auditory Meaning

Alpha oscillations are generally associated with the allocation of cognitive resources, such as suppressing task-irrelevant neural activity and focusing processing on demanding cognitive tasks (Klimesch, 1999). Alpha activity is also closely related to language processing. Upper alpha has been associated with semantic processing, whereas lower alpha is related to attention and alertness. In general, greater cognitive demands are expected to result in lower alpha power. However, alpha power showed almost no difference between the prosody and melody conditions. Therefore, H1 was not supported.

This finding was contrary to the initial expectation that alpha power would be significantly lower in the prosody condition because prosodic speech involves semantic processing, whereas the melodic stimulus does not contain semantic information. Instead, the results suggest that the cognitive demands of the two stimulus conditions were relatively similar. One possible explanation is that both stimuli emphasized familiarity and personal relevance. The prosodic stimulus consisted of a familiar play invitation that children commonly hear in everyday interactions when calling or being called by their friends. As a result, the prosodic sentences may not have required substantial cognitive resources for semantic analysis. Rather than relying on conscious semantic processing, children may have responded through automatic associations between the auditory stimulus and previously established emotional experiences and memories. This interpretation is consistent with the findings of Li et al. (2016), who reported that personally relevant and familiar stimuli are processed more rapidly and tend to activate associative mechanisms. In this context, auditory stimuli may directly activate stored memory representations and emotional content without requiring extensive semantic analysis.

Theta Oscillations, Melodic Structure, and Speech

Although the difference was not statistically significant, theta activity was slightly higher in the prosody condition (the participant's name followed by a play invitation) than in the melody condition. According to previous studies, theta oscillations are associated with the temporal organization of information and episodic memory processing (Nyhus & Curran, 2010). These functions are closely related to the processing of structure in both speech and music.

Language and music both have structural organization, but their structures differ in complexity and underlying rules. Language is generally considered more complex because it follows linguistic principles, including word categories and syntactic rules that organize sentence structure. Music also has its own intrinsic syntactic structure. However, Patel (2003) argued that musical syntax differs fundamentally from language because it does not contain an explicit referential semantic system. As a result, musical syntax is often processed implicitly by untrained listeners, whereas explicit awareness of musical structure generally requires prior musical training (Patel, 2003).

The absence of a significant difference in theta power may also be explained by the characteristics of the prosodic speech stimulus, which was relatively simple, brief, and highly familiar to the participants.

Gamma Oscillations and the Integration of Melodic and Speech Perception

Gamma activity was significantly higher in the prosody condition than in the melody condition. Gamma oscillations are known to mediate perceptual feature binding and cognitive integration in the cortex (Buzsáki, 2006). The interaction of these processes enables the brain to reconstruct the temporal sequence of events (Nyhus & Curran, 2010). In the auditory domain, gamma oscillations play an important role in integrating acoustic information with the information represented by the stimulus (Giraud & Poeppel, 2012). Therefore, the difference in gamma power between Conditions 1 and 2 may be related to the different levels of complexity and integration required by each stimulus.

In the prosody condition, the stimulus contained not only acoustic features, such as pitch, rhythm, and timbre, but also linguistic information, including syntax and semantics (Giraud & Poeppel, 2012). In contrast, the isomorphic melody condition did not contain linguistic features. Its processing was therefore primarily limited to acoustic patterns and temporal structure, including pitch, rhythm, and timbre, without linguistic meaning (Patel, 2012). Although the melodic stimulus had its own intrinsic structure, this structure was isomorphic to the prosodic pattern of the speech stimulus. Therefore, the higher gamma activity observed in the prosody condition likely reflects the greater integration demands imposed by the larger amount of information contained in prosodic speech compared with the isomorphic melody.

Implications of the Findings

The use of personally relevant stimuli in this experiment may have implications for the development of music-based therapeutic interventions for children with developmental language disorders. This possibility is supported by the similar patterns of alpha and theta activity observed across the two stimulus conditions, which may have resulted from the personalized stimulus design, including the use of the participant's own name and highly familiar words. However, this interpretation requires further investigation using more complex stimulus designs, such as stimuli containing a greater variety of words and sentence structures.

Further research is warranted because growing evidence suggests that emotion plays a central role in the relationship between music and language, as emotion recognition is closely associated with word comprehension. According to the review by Szakacs (2006), both music and speech are processed in brain regions that are also involved in motor and emotional processing, particularly within the mirror neuron system. This neural network enables the brain to process emotional information from both music and speech because both forms of communication engage motor-related brain mechanisms. The expressive qualities of human actions, including vocalizations, provide signals about a person's intentions and emotional state. As a result, cross-modal emotional processing, which is essential for effective communication, can occur (de Gelder, 2006). For example, a person's footsteps can provide cues about simple emotional states, such as sadness, anger, or happiness, as demonstrated by Giordano et al. (2014).

This study has several limitations. First, the stimulus design was relatively simple, which limits the ability to determine more precisely the differences between the processing of prosodic speech and isomorphic melody. Second, the study was limited by the EEG recording device. Future studies using multi-channel EEG systems or other more comprehensive neuroimaging techniques may provide more detailed information about the brain regions involved in each stimulus condition. Finally, the sample size was relatively small, and therefore further studies with larger participant groups are needed to improve the generalizability of these findings.

Overall, the present findings support previous studies suggesting that the similarity between music and language processing is mainly found at the domain-general level, whereas their differences become more apparent during more complex cognitive processing. Consistent with previous literature, this domain-general processing may arise because both music and speech involve the processing of emotional information conveyed through shared acoustic features. Furthermore, the findings suggest that music can be designed to better support therapeutic interventions, particularly when the goal is to improve the perception of emotional information conveyed in spoken language. Therefore, designing musical stimuli that incorporate personally relevant and emotional elements may increase the effectiveness of music-based interventions for language disorders. Nevertheless, these implications should be examined further using more complex experimental designs and more advanced neurophysiological recording techniques.

CONCLUSIONS

The findings of this study indicate that the overlap between music and language processing is only partial. This overlap, or the sharing of neural resources, is reflected in the absence of significant differences in alpha and theta oscillations between the prosody and melody conditions. These results suggest that both stimuli engage relatively similar neural resources for temporal and emotional processing, particularly when the stimuli are familiar and personally relevant. However, the significant difference observed in gamma activity indicates that prosodic speech requires more complex information integration than isomorphic melody because it also involves linguistic features, such as syntax and semantics.

ACKNOWLEDGMENTS

This research was funded by the Ministry of Higher Education, Science, and Technology of the Republic of Indonesia through the Institute for Research and Community Service (LPPM), Indonesian Institute of the Arts (ISI) Yogyakarta, under the 2025 DIPA ISI Yogyakarta Research Grant (Research Agreement No. 4388/IT4.6.1/DT/2025). The authors would like to express their sincere gratitude to Kanisius Kembaran Elementary School, Kasihan, Bantul, Special Region of Yogyakarta, Indonesia, for facilitating this research. The authors also thank the participating children, their parents or legal guardians, and the teachers for their valuable cooperation and support throughout the data collection process.

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