The Effect of Music Training on Brain Pre-attentive Processing

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Abstract

Pre-attentive processing is a cognitive process that occurs prior to attention and does not depend on consciousness, reflecting the brain' s unconscious, automatic processing of stimuli. Mismatch negativity (MMN) is the most commonly used index for studying pre-attentive processing. Reduced MMN amplitude has become an important clinical indicator for psychiatric disorders such as schizophrenia and depression. Research paradigms for MMN mainly include the classic oddball paradigm and the multi-feature paradigm, among others. Music training has important effects on human brain structure and function, demonstrating significant efficacy in increasing gray matter volume and improving attention and memory functions. Music training also has significant effects on MMN, which are manifested in paradigms constructed from various sound features. Future research should further compare the effects of Eastern and Western music on MMN, explore paradigms with greater ecological validity, and reveal the effects and mechanisms of music training on MMN in older adults.

Full Text

The Effects of Music Training on Pre-attentive Processing in the Brain

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Abstract: Pre-attentive processing is a cognitive process that occurs prior to attention and operates independently of consciousness, reflecting the unconscious and automatic aspects of brain processing. Mismatch negativity (MMN) is the most commonly used indicator for studying pre-attentive processing. Reduced MMN amplitude has become an important clinical marker for psychiatric disorders such as schizophrenia and depression. The main research paradigms for MMN include the classic oddball paradigm and the multi-feature paradigm. Music training has profound effects on human brain structure and function, significantly increasing gray matter volume and improving attention and memory functions. Music training also exerts significant effects on MMN, as demonstrated across paradigms constructed with various acoustic features. Future research should further compare the effects of Eastern and Western music on MMN, explore paradigms with greater ecological validity, and reveal the impact and mechanisms of music training on MMN in elderly populations.

Keywords: music training; pre-attentive processing; MMN

1. Introduction

Pre-attentive processing refers to the early processing of stimuli that occurs before conscious attention, providing an informational foundation for subsequent attentional selection. This stage does not require purposeful, conscious attention, as initial information is analyzed during the pre-attentive phase before entering the attentional stage. During this phase, the brain primarily detects basic features of stimuli (Logan, 1992).

Mismatch negativity (MMN) is an effective indicator that reflects the level of pre-attentive processing. It is an event-related potential elicited by stimulus change across multiple sensory modalities, including auditory, visual, and somatosensory systems. When a small number of low-probability deviant stimuli are presented within a series of repeatedly occurring high-probability standard stimuli, the deviant stimuli elicit a larger negative potential deflection than the standard stimuli, which is known as MMN (Näätänen, Gaillard, & Mäntysalo, 1978; Näätänen, Tervaniemi, Sussman, Paavilainen, & Winkler, 2001). MMN was first introduced by Näätänen and colleagues in 1978 (Näätänen et al., 1978). In a dichotic listening paradigm, researchers presented standard and deviant stimuli randomly to both ears while participants attended only to one ear. The results showed that deviant stimuli elicited larger negative waves than standard stimuli regardless of whether they were presented in the attended or unattended ear. The difference wave obtained by subtracting the brainwave amplitude elicited by standard stimuli from that elicited by deviant stimuli constitutes MMN. In humans, MMN typically appears within a time window of 100–250 ms post-stimulus, with the largest amplitude recorded at frontal electrodes (using mastoids or the nose tip as reference) (Sams, Paavilainen, Alho, & Näätänen, 1985).

MMN reflects the automatic processing of stimuli without requiring attentional engagement, making it possible to record under conditions of unconsciousness such as sleep (Chen, Sung, & Cheng, 2016), coma (Juan et al., 2016; Wang et al., 2018), and in individuals who cannot communicate effectively, such as infants and psychiatric patients (Näätänen et al., 2012; Zinke, Thöne, Bolinger, & Born, 2018). Research has also shown that MMN is sensitive to music-related discrimination learning (Näätänen, Schröger, Karakas, Tervaniemi, & Paavilainen, 1993) and to individuals' musical expertise (Vuust, Liikala, Näätänen, Brattico, & Brattico, 2016). Therefore, recording MMN elicited by sound features related to musical elements (pitch, melody, rhythm) may serve as an objective measure of musical discrimination ability.

Music performers require complex cognitive and operational abilities, including note recognition, coordination of spatiotemporal visual information, good working memory, and the capacity to comprehend musical meaning and emotion (Norton et al., 2005). Studies have found that compared to non-musicians, musicians show significantly increased gray matter volume in brain regions such as the inferior temporal gyrus, transverse temporal gyrus, inferior frontal gyrus, and precentral gyrus (Gaser & Schlaug, 2003; Hyde et al., 2009; Schneider et al., 2002). Additionally, music training has been shown to facilitate non-musical cognitive skills, including language development (Kraus et al., 2014), mental rotation (Bhattacharya, Petsche, Feldmann, & Rescher, 2001), and sensorimotor information integration (Luo et al., 2012). As a cognitive process, whether pre-attentive processing is influenced by music training has attracted considerable research attention. Current studies have primarily focused on comparing MMN differences between musicians and non-musicians across various parameters, including pitch (Nan et al., 2018), timbre (Meyer et al., 2011), chords (Virtala, Huotilainen, Partanen, & Tervaniemi, 2014), rhythm (Zhao, Lam, Sohi, & Kuhl, 2017), and melody (Fujioka, Trainor, Ross, Kakigi, & Pantev, 2004). This paper summarizes these studies to provide an important reference for the rational application of music training to improve brain function.

2. Research Paradigms for Musical MMN

The classic paradigm for obtaining MMN is the oddball design (May et al., 1999; Näätänen et al., 1978). This approach uses pure tones as stimuli, inserting low-probability deviant stimuli (D) within a series of repeatedly presented standard stimuli (S), where D differs from S in only one feature while all other features remain identical. This paradigm is the most widely applied. In 2004, Näätänen and colleagues proposed a new paradigm—the multi-feature MMN paradigm (Näätänen, Pakarinen, Rinne, & Takegata, 2004)—which presents multiple types of acoustic feature changes within the same sound sequence, including pitch, loudness, duration, and sound source location. In essence, it is a paradigm combining one S with multiple Ds, as shown in Figure 1a [Figure 1: see original paper]. Every other S is followed by a D. The most prominent advantage of this paradigm is its ability to simultaneously obtain MMNs elicited by five different acoustic features within the same time traditionally required to obtain only one MMN, making it possible to detect multiple different auditory discrimination abilities in a single experiment. This not only substantially reduces experimental time but also enhances detection sensitivity.

The multi-feature paradigm provides a framework for integrating different acoustic features into musical contexts. Recording music-related sound features within a musical background offers an objective means of assessing individual musical abilities. The musical multi-feature MMN paradigm uses four-note Alberti bass patterns as stimuli (Vuust et al., 2011), incorporating six types of sound changes related to music processing across different genres: pitch, intensity, timbre, sound source location, rhythm, and glissando. Alberti bass is a fundamental and common accompaniment pattern in music. The difference between D and S lies in the third note of each four-note group. For example, in D patterns, the third note is 24 cents lower in pitch than the third note in S patterns, while the other three notes remain identical, as shown in Figure 1b. The musical multi-feature MMN paradigm is highly similar to real music, thus possessing higher ecological validity than traditional measurement methods. Moreover, the test can be completed within 20 minutes, making it highly suitable as an objective measure for music-related auditory development.

Figure 1. (a) Schematic diagram of the multi-feature paradigm. S represents standard stimuli, while D1, D2, etc. represent different deviant stimuli. (b) Multi-feature paradigm using Alberti Bass as stimuli. The red box (left) and green box (right) each contain four-note melodies; the third note in the red box is the standard stimulus, while the third note in the green box is the deviant stimulus. Except for the third note, the corresponding notes in the other three positions are identical (adapted from Vuust et al., 2011).

3. Effects of Music Training on MMN

Research indicates that individuals with music training do not show significant differences from those without training in pre-attentive processing of simple sound stimuli. For example, Koelsch and colleagues found that when stimuli were pure tone pitch changes, both violinists and non-musicians produced MMN, with no significant difference in amplitude between the two groups (Koelsch, Schröger, & Tervaniemi, 1999). Tervaniemi and colleagues manipulated the degree of pitch difference (small, medium, large) and also failed to find MMN amplitude differences between musicians and non-musicians (Tervaniemi, Just, Koelsch, Widmann, & Schröger, 2005). Researchers suggest this may be because pure tone stimuli are relatively simple and easy to discriminate for both musicians and non-musicians, creating a ceiling effect. Therefore, during the pre-attentive stage, musicians' expertise does not confer an advantage in facilitating neurocognitive processing. However, some studies have found that when stimuli involve changes in sound intensity or source location, musicians' MMN amplitudes are significantly larger than those of non-musicians (Tervaniemi, Castaneda, Knoll, & Uther, 2006). Additionally, in terms of latency, individuals with music training show significantly shorter MMN latencies for pure tone stimuli than those without training (Nikjeh, Lister, & Frisch, 2009). Overall, however, music training has relatively minor effects on individuals' ability to discriminate basic acoustic features at the pre-attentive processing level. Music differs from simple sound stimuli, which contain only basic physical features such as frequency, loudness, and duration. Music consists of individual notes organized according to specific rules that create intervals, melodies, rhythms, and meters. These melodic and rhythmic elements make musical attributes more complex than single pure tone pitches or durations. Consequently, it can be hypothesized that individuals with and without music training may show differences in pre-attentive processing of these complex musical features.

3.1 Differences Based on Interval Features

An interval refers to the pitch relationship between notes. Each note's frequency determines its pitch, and the distance in pitch between two notes that appear sequentially or simultaneously in a melody constitutes an interval. Chords represent an important form of intervals, created by superimposing a group of sounds with specific interval relationships. Changing the stacking order of notes within a chord creates chord inversions. Chords can be divided into major and minor chords. In Western music, major chords are primarily associated with pleasant emotions, while minor chords are associated with sad or calm emotions.

Virtala and colleagues used an MMN paradigm with interval changes (S as major chords, D as minor chords and inverted major chords) to investigate the effects of music training on pre-attentive processing (Virtala, Huotilainen, Putkinen, Makkonen, & Tervaniemi, 2012). The results showed that music-trained children exhibited significant MMN responses to minor chords, whereas untrained children did not. However, neither group showed significant MMN responses to inverted major chords. This suggests that music training facilitates pre-attentive processing of chord changes. Subsequently, Virtala and colleagues (2014) divided stimuli into three types: 250 ms sine tones, 650 ms sine tones, and 650 ms piano tones, examining MMN responses to minor chords and inverted major chords in adult musicians and non-musicians under these three conditions. The findings revealed that minor chords and inverted major chords elicited significant MMN in musicians across all three conditions, while non-musicians showed no MMN in any condition. This demonstrates that individuals with long-term music training possess superior discrimination abilities for complex musical stimuli at the pre-attentive processing level.

Researchers have also investigated the cerebral lateralization of pre-attentive processing of chord changes. Tervaniemi and colleagues used major chords as S and minor chords as D, comparing MMN differences among musicians, non-musicians with strong musical abilities, and ordinary non-musicians. They found that the left hemisphere MMN responses in the first two groups were significantly larger than those in ordinary non-musicians (Tervaniemi, Sannemann, Nöyränen, Salonen, & Pihko, 2011). These results indicate that although MMN elicited by sound stimuli typically shows right hemisphere dominance, processing complex, music-related sound stimuli requires involvement of both hemispheres.

Major and minor chords are the most common chord types in Western music, collectively known as consonant chords. Additionally, researchers have defined dissonant chords and mistuned chords (Brattico et al., 2009). These two chord types appear infrequently in Western music and are even rarer in the experience of non-musicians. Mistuned chords have the smallest pitch difference from major chords, while dissonant chords have a slightly larger difference. Using magnetoencephalography (MEG), Brattico and colleagues found that dissonant and mistuned chords elicited significantly larger MMNm amplitudes in musicians than in non-musicians, whereas minor chords did not show significant group differences. Correlation analyses revealed that MMNm amplitudes elicited by dissonant and mistuned chords were significantly positively correlated with the duration of music training, meaning that longer training was associated with more pronounced MMN. These results demonstrate that music training also promotes pre-attentive processing of atypical musical chords.

3.2 Differences Based on Melodic Features

Musical melody involves two elements: melodic contour and interval relationships. Melodic contour refers to the direction of adjacent notes in a melody—whether the flow moves from low to high pitches (ascending) or from high to low pitches (descending). Interval relationships represent the degree of this direction, indicating the actual pitch distance between adjacent notes. Only through the combination of these two elements can each note comprising a melody be determined. The ability to recognize melodic contour and interval relationships affects overall melody perception.

Research has shown that musicians exhibit higher levels of pre-attentive processing for changes in melodic contour and interval relationships compared to non-musicians. For instance, Pantev and colleagues' findings indicated that when a descending melody was inserted into a series of ascending melodies without changing interval relationships, musicians produced significantly larger MMNm amplitudes than non-musicians. Similarly, when melodic contour remained unchanged but the interval relationship between the last two notes was altered, musicians' MMNm amplitudes were also significantly larger (Pantev et al., 2003). Subsequently, Fujioka and colleagues added a control condition (pure tones) to their study, using a traditional oddball paradigm where S and D were two pure tones that had appeared previously. The results showed that under control conditions, musicians and non-musicians did not differ significantly in pitch MMNm amplitude. However, musicians' MMNm elicited by melodic contour deviants and interval deviants was significantly larger than that of non-musicians (Fujioka et al., 2004).

3.3 Differences Based on Temporal Structure Features

Rhythm and meter are important attributes of music, both reflecting the temporal structure in music. In music, rhythm refers to the regular pattern of strong and weak beats formed by notes of varying durations, while meter refers to the phenomenon of regularly recurring strong and weak beats with equal note values. Geiser and colleagues investigated the effects of music training on MMN elicited by meter changes (Geiser, Sandmann, Jäncke, & Meyer, 2010), using stimuli shown in Figure 2 [Figure 2: see original paper]. In S patterns, all notes had equal intensity. Two types of D were used: one increased the intensity of the first beat in the final measure (meter-congruent deviant, mcD), while the other advanced the first beat of the final measure by half a beat and increased its intensity (meter-incongruent deviant, miD). The study found that musicians showed significantly higher MMN responses to miD than non-musicians, but lower MMN responses to mcD. This suggests that musicians are more likely to develop expectations for meter, making them more sensitive to violations of these expectations, such as those represented by miD.

Vuust and colleagues (2009) selected two types of rhythmic deviant stimuli. One deviant had a small difference from the standard rhythm (sII condition), representing a low degree of expectancy violation. The other deviant had a larger difference from the standard rhythm and violated metrical regularity (sIII condition), representing a high degree of expectancy violation. The results showed that both musicians and non-musicians exhibited significantly larger MMNm amplitudes in the sIII condition compared to the sII condition. Moreover, musicians' MMNm amplitudes were significantly larger than those of non-musicians in both conditions.

Figure 2. Stimulus materials. The first line shows the standard stimulus, consisting of three measures where each note has equal intensity. The long gray bars below the notes represent a sound duration of 600 ms, while short gray bars represent 300 ms. The second line shows the meter-congruent deviant stimulus, where each note has the same duration as the standard stimulus but with increased intensity on the first beat of the final measure (indicated by the arrow). The third line shows the meter-incongruent deviant stimulus, where the first note of the final measure is intensified and advanced by 300 ms (indicated by the arrow) (adapted from Geiser et al., 2010).

4. Different Music Training Strategies

Music training can effectively enhance individuals' pre-attentive processing of complex musical features. Various training strategies exist: some musicians employ auditory training strategies, such as jazz musicians who possess greater abilities in improvisation and discrimination of pitch and rhythm; others use score-reading training strategies, such as classical musicians who develop strong sight-reading abilities; and some focus more on rhythm and sound localization training, such as rock musicians. Based on this, researchers have hypothesized that musicians trained with different strategies may also show differences in pre-attentive processing levels for different musical features (Vuust, Brattico, Seppänen, Näätänen, Tervaniemi, et al., 2012).

4.1 Cross-Sectional Studies

Tervaniemi and colleagues divided 20 mixed participants (musicians and non-musicians) into two groups based on behavioral test performance: an accurate melody discrimination group (precise group) and an inaccurate melody discrimination group (non-precise group). The precise group consisted of 8 trained musicians (jazz or pop musicians), while the non-precise group included 12 participants (5 classical musicians and 7 non-musicians). After a single 12-minute training session testing melodic contour MMN, neither group showed significant MMN. However, after the second and third training sessions, the precise group exhibited significant MMN, while the non-precise group still did not. Researchers attributed this to the use of score-free auditory training, similar to the training approach of jazz musicians, which enabled the precise group to produce significant MMN. In contrast, classical musicians in the non-precise group typically receive visual training in score-reading, making brief auditory training insufficient to significantly improve performance on melodic MMN measures (Tervaniemi, Rytkönen, Schröger, Ilmoniemi, & Näätänen, 2001).

Vuust and colleagues used a multi-feature musical paradigm to compare jazz, classical, and rock musicians with non-musicians (Vuust, Brattico, Seppänen, Näätänen, & Tervaniemi, 2012). Deviant stimuli included six types: pitch, location, timbre, intensity, glissando, and rhythm. The results showed that jazz musicians exhibited significantly larger MMN responses to glissando deviants than other groups, and significantly larger MMN responses to pitch deviants than non-musicians. The authors suggested that these results stem from different learning strategies employed by different types of musicians. Jazz performance requires strong auditory discrimination abilities and improvisation skills, making performers sensitive to subtle changes in pitch and intensity. Glissando is a technique commonly used in improvisation, rendering jazz musicians more sensitive to this element than others. Tervaniemi and colleagues (2006) also supported this view, finding that amateur rock musicians showed significantly larger MMN amplitudes elicited by location deviants than non-musicians. This may be because individuals trained in rock music are better than average at coordinating and integrating sounds from different locations and instruments.

These studies demonstrate that music training enhances individuals' ability to extract abstract rules, enabling automatic detection of rule-violating stimuli. Moreover, the facilitative effect of music training on pre-attentive processing is specific: different training methods can improve pre-attentive processing levels for different stimuli. Therefore, educational processes should employ comprehensive music training combining multiple approaches to improve learners' cognitive abilities.

4.2 Longitudinal Studies

The aforementioned studies involve cross-sectional research comparing professional musicians with untrained individuals. Relatively fewer longitudinal studies have examined improvements in pre-attentive processing through music training. Zhao and Kuhl conducted a 4-week music intervention comprising 12 sessions with 9-month-old infants (Zhao & Kuhl, 2016). The infants listened to music in triple meter and moved to the beat with the help of caregivers. Control group infants did not listen to music but played with toys freely. Subsequent testing of MMNm elicited by temporal structure changes (standard stimulus: repeated triple meter; deviant stimulus: occasional duple meter inserted) revealed that the music intervention group showed greater sensitivity to temporal structure changes, with larger MMNm amplitudes than the control group.

Putkinen and colleagues conducted a longitudinal study of children who began music training at age 7, recording their MMN at four age stages: 7, 9, 11, and 13 years (Putkinen, Tervaniemi, Saarikivi, Ojala, & Huotilainen, 2014). In the chord paradigm, both musicians and non-musicians showed increased MMN amplitude with age, but musicians' MMN increased significantly more than non-musicians' . In the multi-feature paradigm, both groups showed age-related increases in MMN amplitude for location, frequency, stimulus onset asynchrony, and intensity, but only the location MMN condition showed greater age-related increases in musicians than non-musicians.

Music training not only promotes cognitive development in infants and children but can also enhance pre-attentive processing levels in adults. Lappe and colleagues found that non-music majors showed significant MMN amplitude increases after short-term music training (Lappe, Herholz, Trainor, & Pantev, 2008). Participants were divided into two groups: one received piano training (SA group), combining sensory and motor training, while the other received only auditory training (A group), listening to music played by the SA group and evaluating its correctness. Training consisted of eight 25-minute sessions within two weeks. Within-subject comparisons revealed that post-training MMN amplitudes in the SA group were significantly higher than pre-training, while the A group showed no significant difference. These results indicate that sensorimotor combined training is more effective than auditory training alone for improving pre-attentive processing levels.

Compared to cross-sectional studies, longitudinal studies provide stronger evidence for causal relationships by better demonstrating changes in brain pre-attentive processing resulting from music training. Overall, music training can enhance pre-attentive processing levels across different age groups, with greater improvements associated with longer training duration, particularly when using sensorimotor combined training. Therefore, music instruction should employ more sensorimotor combined training methods to enhance learners' pre-attentive processing abilities.

5. Summary and Outlook

In summary, music training exerts clear facilitative effects on pre-attentive processing in the brain, with different effects across stimulus types: minimal promotion of MMN for simple sound stimuli but substantial promotion for complex sound stimuli. This suggests that automatic processing of simple stimuli does not require musical knowledge, whereas discrimination of music-related complex stimuli and automatic processing of abstract rules depend to some extent on music training. Furthermore, different training methods and learning durations produce different effects on MMN. Music is a complex whole, and current research paradigms are better suited for studying pre-attentive processing of relatively simple stimuli. Given music' s complexity, these paradigms require further improvement to make stimuli more similar to real music, thereby achieving more ecologically valid experimental results.

Music is a product of human evolution, containing rich cultural information and reflecting complex and diverse human emotions. Individuals' preferences for and sensitivity to music may differ across emotional states, and the process of music training itself involves comprehension of musical emotion. Research has found that music training can affect people' s emotional perception (Di Mauro, Toffalini, Grassi, & Petrini, 2018), but whether it enhances pre-attentive processing related to musical emotion and whether it improves pre-attentive processing of emotional information in meaningless speech and language requires further investigation. Therefore, to explore the relationship among music training, emotion, and pre-attentive processing levels, future research could compare MMN responses to musical and linguistic emotion between musicians and non-musicians (cross-sectional design) and examine the effects of long-term versus short-term music training on emotional MMN (longitudinal design). Such results could not only verify the influence of music training on language pre-attentive processing abilities but also provide insights for music therapy and alleviation of emotional disorders. Additionally, current research has focused primarily on Western music, with insufficient in-depth comparison of different music types across cultural backgrounds. For instance, Chinese classical music and Western music differ in many musical elements. Future research could use Eastern and Western music as stimulus materials to study MMN differences between individuals trained in Western versus traditional music. These studies would help reveal cultural differences between East and West and identify the advantages of different types of music training.

Finally, it should be noted that normal individuals' pre-attentive processing levels are affected by age. Evidence indicates that MMN amplitude diminishes with age (Ruzzoli, Pirulli, Brignani, Maioli, & Miniussi, 2012). The underlying mechanisms warrant attention. Studies have found that in target detection tasks, older adults show poorer adaptation to repeatedly presented stimuli than younger adults (Grady, Yu, & Alain, 2008), which may contribute to smaller MMN amplitudes. Further research has suggested that decreased frontal control function in older adults may underlie MMN amplitude reduction. At the neuronal population level, decreased frontal control function may result from disrupted excitation-inhibition balance in frontal pyramidal cells and increased connectivity between temporal and frontal lobes (Cooray, Garrido, Hyllienmark, & Brismar, 2014). These studies provide neurobiological explanations for age-related MMN amplitude changes. However, for individuals with music training, whether music training can compensate for age-related declines in hearing and auditory discrimination abilities, whether it can promote the maintenance and enhancement of other cognitive abilities (such as language perception), and whether these compensatory effects are reflected in MMN amplitude changes require further verification. Therefore, future research should employ two-factor designs comparing music training versus no training and older versus younger adults to address these questions and reveal the relationship between music training duration, age of training onset, and MMN changes. Additionally, combining functional magnetic resonance imaging and other techniques to investigate the brain mechanisms underlying MMN amplitude changes induced by music training would be valuable. Such research holds important theoretical and practical significance for improving brain function in older adults.

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Note: Figure translations are in progress. See original paper for figures.