Received: 17 November 2021 | Revised: 2 March 2022 | Accepted: 22 March 2022
DOI: 10.1002/jdn.10181

RESEARCH ARTICLE

INTERNATIONAL JOURNAL OF DEVELOPMENTAL NEUROSCIENCE ISDN WILEY

The relationship between acoustic and musical pitch processing in adolescents

Benjamin Rich Zendel[1,2,3] | **Özgen Demirkaplan**[1] | **Geneviève Mignault-Goulet**[3] | **Isabelle Peretz**[3]

[1]Faculty of Medicine, Memorial University of Newfoundland, St. John's, Canada

[2]Aging Research Centre – Newfoundland and Labrador, Grenfell Campus, Memorial University, Corner Brook, Canada

[3]The International Laboratory for Brain Music and Sound Research (BRAMS), Département de psychologie, Université de Montréal, Corner Brook, Canada

Correspondence
Benjamin Rich Zendel, Faculty of Medicine, Memorial University of Newfoundland, St. John's, Canada.
Email: bzendel@mun.ca

Funding information
Canadian Institutes of Health Research; CIHR; Canada Research Chairs

Abstract

Amusia is defined as a difficulty processing the tonal pitch structure of music such that an individual cannot tell the difference between notes that are in-key and out-of-key. A fine-grained pitch discrimination deficit is often observed in people with amusia. It is possible that an intervention, early in development, could mitigate amusia; however, one challenge identifying amusia early in development is that identifying in- and out-of-key notes is a metacognitive task. Given the common co-occurrence of difficulties with pitch discrimination, it would be easier to identify amusia in developing children by using a pitch change detection task. The goal of this study was to explore the behavioural and neurophysiological profiles of adolescents with poor pitch processing (Poor PP) abilities compared with those with normal pitch processing (Normal PP) abilities. Neurophysiologically, the Poor PPs exhibited a similar event-related potential (ERP) profile to adult amusics during both acoustic and musical pitch discrimination tasks. That is, early ERPs (ERAN, MMN) were similar in Poor PPs compared with Normal PPs, whereas late positivities (P300, P600) were absent in Poor PPs, but present in Normal PPs. At the same time, behavioural data revealed a double dissociation between the abilities to detect a pitch deviant in acoustic and musical context, suggesting that about a third of the children would be missed by selecting a fine-grained acoustic pitch discrimination task to identify the presence of amusia in early childhood.

KEYWORDS
adolescents, amusia, ERAN, event-related potentials, MMN, music, P300, P600, pitch discrimination

1 | INTRODUCTION

The ability to discriminate tones based on frequency is a fundamental auditory process that is used in both music and speech which reaches adult-like levels before the age of 10 (Thompson et al., 1999). Using a single tone of 1000 Hz that was 200 ms long, Thompson et al. (1999) found that children aged 9–11 and adults could discriminate tones that differed by as little as 5 Hz, or about 8.6 cents. Yet, a small percentage of adolescents exhibit significant difficulties discriminating tones that differ by as much as 100 cents (e.g. Mignault Goulet et al., 2012). In adults, the lack of ability to discriminate between tones that differ by 100 cents is considered one of the central deficits in a music processing disorder known as congenital amusia (Hyde & Peretz, 2004; Peretz, 2016). Congenital amusia effects about 1.5% of the adult population, and, in addition to the pitch discrimination deficit, is characterized by an inability to recognize familiar melodies, and difficulty identifying when notes in a melody are out-of-key (Peretz, 2016; Peretz & Vuvan, 2017; Vuvan et al., 2015). Critically, congenital amusia is not associated with any other hearing disorders; however, recent research has found some degree of comorbidity with dyslexia (Couvignou & Kolinsky, 2021; Couvignou et al., 2019). Moreover, amusia is not due to lack of exposure to music in childhood (Mignault Goulet et al., 2012) and likely has a genetic source (Peretz et al., 2007; Peretz & Vuvan, 2017). Previous work has shown that adolescents with pitch processing difficulties exhibit a similar neurophysiological profile as adults during a pitch change detection task (Mignault Goulet et al., 2012). Little work has been done to connect this basic pitch discrimination deficit in adolescents to a music processing deficit seen in adults with amusia. Accordingly, the goal of this study was to examine if adolescents with poor pitch processing abilities (Poor PP) exhibit a similar behavioural and neurophysiological profile as adults with poor pitch processing abilities when asked to detect out-of-key notes in a melody.

The ability to detect an out-of-key note in a melody relies on implicit knowledge of tonal structure and the ability to consciously access knowledge of tonal structure. Tonal structure is the hierarchical relationship between notes, where some notes are perceived as being a better fit than others in a musical context (Krumhansl & Kessler, 1982). In the developmental process, knowledge of tonal structure is acquired implicitly through exposure to music (Bigand & Poulin-Charronnat, 2006). Despite the implicit acquisition of tonality, musical tasks, such as detecting an out-of-key note, require active access to tonal representations (Cuddy & Badertscher, 1987). Recent work in amusia suggests that some implicit aspects of tonal processing remain intact (Omigie et al., 2012; Peretz et al., 2009; Tillmann et al., 2012). For example, the mismatch negativity (MMN) evoked by small pitch deviants is little effected by amusia in adults (Moreau et al., 2013) and adolescents (Mignault Goulet et al., 2012), even though individuals with amusia cannot consciously detect those differences. In both adults and adolescents with amusia, P3-type responses were attenuated to small pitch changes, paralleling the behavioural differences between people with amusia and controls. Like the MMN, the early-right anterior negativity (ERAN), evoked by notes that violate the tonal structure of a melody, was similar in adults with amusia compared with controls when participants were not attending to the tonal structure of the melody, whereas late positive responses to violations of tonality when the participant was attending to the melody (i.e. P600) were absent in adults with amusia (Peretz et al., 2009; Zendel et al., 2015). We are unaware of any research about the ERAN/P600 profile in adolescents who have poor pitch processing abilities and how this profile impacts their ability to detect melodic deviants. More generally, the ERP profile obtained by pitch and melodic deviants has never been compared in the same participants.

Characterizing the amusic profile in adolescents is critical, as it may be possible to design a music-based intervention that could mitigate amusia, and this type of intervention would likely be most effective at earlier stages of development (Peretz, 2016; Peretz et al., 2009). There is evidence that music training is associated with enhanced frequency discrimination abilities (Kishon-Rabin et al., 2001; Micheyl et al., 2006; Parbery-Clark et al., 2009; Spiegel & Watson, 1984), improved ability to detect out-of-tune/key notes (Besson & Faita, 1995; Zendel & Alexander, 2020) and improved cognitive abilities (Schellenberg, 2004, 2006). Therefore, a music-based intervention could potentially be successful at improving music perception in children with music processing deficits.

One of the challenges with starting early interventions is that children and adolescents with amusia may not realize that they have amusia until they are much older because musical pitch discrimination is a metacognitive task that requires the ability to interpret ongoing notes in a melody as being in- or out-of-key. Implicit knowledge of tonality is present very early in development, likely between birth (Perani et al., 2010) and 4 years of age (Trainor & Hannon, 2013); however, identification of in- and out-of-key notes requires conscious access to that implicit knowledge. A lack of conscious access to implicit knowledge of tonal structure is likely the core deficit observed in amusia (Peretz, 2016). At the same time, we are unaware of research that identifies an age at which the developing child can explicitly identify in- and out-of-key notes with confidence. Trainor and Trehub (1994) showed that the ability to detect out-of-key notes emerges sometime between 5 and 7 years of age. At the same time, 7-year-old children were less able to detect an out-of-key note when compared to adults (Trainor & Trehub, 1994), suggesting that this ability is not fully developed until well after age 7. Despite this, the Montreal Battery of Evaluation of Musical Abilities (MBEMA; Peretz, 2013) can successfully discriminate musical abilities in 6- to 8-year-olds and may be able to identify potential cases of amusia; however, it may be too late for rehabilitation at this age. It is therefore difficult to identify younger people with amusia using musical pitch discrimination alone.

The goal of the current study was to connect acoustic pitch discrimination abilities in adolescents to musical pitch discrimination abilities in order to highlight the importance of this connection during development. Moreover, if this connection exists in adolescents, then a pitch discrimination task could be used to identify potential cases of amusia in younger children. Pitch discrimination tasks require much less metacognitive awareness compared with tasks that require detection of melodic violations. That is, it is easier to explain to a young child to report if tones were the same or different, compared with asking them if a note fits in the melodic context.

Accordingly, we took a sample of healthy adolescents and split the group based on their ability to discriminate a 25-cent pitch deviant. This created two groups of participants, Normal Pitch Processors (Normal PP/NPP; participants could reliably discriminate tones that differed by 25 cents) and Poor Pitch Processors (Poor PP/PPP; participants could not reliably discriminate tones that differed by 25 cents). Additionally, we recorded EEG during both an acoustic pitch discrimination task and a musical pitch discrimination task in order to observe how poor pitch processing impacts the ability to detect a musical deviant, and to characterize the relationship between ERPs that are generally 'spared' in amusia (i.e. MMN and ERAN) and those that are impaired in amusia (i.e. P3 and P600).

2 | METHOD

2.1 | Participants

A total of 18 adolescent participants took part in this study. All participants provided oral consent to participate and a parent or legal guardian completed written informed consent and were provided an honorarium for their time. The study was approved by the Research Ethics Council for the Faculty of Arts and Sciences at the Université de Montréal. Participants were recruited through emails sent to various mailing lists (schools, summer camps, etc.), from lists of participants from past studies. Participants were categorized as either poor pitch processors (Poor PP/PPP; $N = 9$) or normal pitch processors (Normal PP/NPP; $N = 9$) by a median split based on their accuracy in detecting a 25-cent pitch change in a stream of five otherwise identical tones (see *pitch change detection task*). Previous work has shown that pitch discrimination abilities reach adult like levels by age 10 (Mishra et al., 2021; Moore et al., 2011). A study using the same paradigm in normal adults found that healthy older adults had a hits minus false alarm (H-FA%) rate of 87.7% (Moreau et al., 2013; H-FA% was calculated from accuracy and false alarm rates reported in the paper). In the current study, accuracy was defined as the percentage of the number of hits (i.e. correctly identifying a 25-cent pitch change) minus the percentage of false alarms (i.e. reporting a pitch change, when all five tones were identical). Accuracy for the Normal PPs was 79.7% (SD = 11.8), and for the Poor PP was 31.2% (SD = 15.0); the difference reached statistical significant, $t(16) = 7.61$, $p < 0.001$.

Participants were matched in terms of age (13.3 [NPP] vs 12.6 [PPP], $p > 0.05$), gender (8 female [NPP]; 7 female [PPP]), and their average school grades (84.8% [NPP] vs 77.9% [PPP], $p > 0.05$). Interestingly, the PPP and NPP groups were also matched on the scores from the Montreal Battery of Evaluation of Amusia (MBEA) (Peretz et al., 2003; NPP = 23.3; PPP = 22.9; $p = 0.79$). Participants were also asked if they liked music, if they liked to sing and if they liked to dance using a 4-point scale ranging from 1 [*no, not at all*] to 4 [*yes, very much*]. There were no differences between the groups for these questions ($p > 0.05$). All participants were right-handed, had normal pure-tone audiometry (<25 dB HL for 500–4000 Hz), had no neuropsychological disorder according to their parents (ADHD, dyslexia, etc.) and spoke French fluently (15 were native French speakers, two were native Arabic speakers, and one was a native Romanian speaker). No participant had extracurricular musical training at the time of the study, but two participants (1 NPP and 1 PPP) reported that they had received group music lessons previously (for more than 6 months, but no more than a year on an instrument). All participants' parents were working, most of them in professions that require training/education, suggesting that most participants were from middle to high socio-economic backgrounds.

2.2 | Materials and procedures

Each participant attended two sessions. In the first session, each participant completed the Montreal Battery for the Evaluation of Amusia (MBEA; Peretz et al., 2003), the vocabulary test from the WISC-IV (Wechsler, 2003), the inhibition tests from the NESPY-II (Korkman et al., 2007), the Hearing in Noise Test adapted for Canadian French (HINT; Nilsson et al., 1994), the Grooved Pegboard Test (Kløve, 1963) and a questionnaire about their musical background and habits (see Table 1). The second session was held on a different day. In the second session, participants completed the EEG tasks described below.

INTERNATIONAL JOURNAL OF DEVELOPMENTAL NEUROSCIENCE

TABLE 1 Participant demographics

Group	Gender	Age	SchoolGrade[a]	WISC_Vocab[b]	Grooved_Dom[c]	Grooved_NonDom[c]	NESPY_Inhib[b]	NESPY_Switch[b]	HINT[d]	MBEA
NPP	8 female 1 male	13.3 (1.7)	84.8 (8.2)	10.7 (3.0)	62.9 (8.9)	69.9 (16.1)	21.4 (3.1)	41.0 (6.5)	3.4 (0.6)	23.3 (3.5)
PPP	7 female 2 male	12.6 (1.4)	77.9 (7.7)	11.0 (2.2)	61.3 (5.9)	71.9 (10.0)	26.8 (7.8)	44.6 (11.9)	3.4 (1.0)	22.9 (3.3)

[a]Average grade reported by parents (%).
[b]Scaled score.
[c]Time to completion in seconds.
[d]72% thresholds in decibels signal-to-noise ratio (dB SNR).

2.3 | EEG tasks

After being fitted with an EEG cap (see following text), participants completed three tasks in the following order: active acoustic pitch change detection task followed by passive listening of stimuli from the acoustic pitch change task and then a musical pitch change detection task. All tasks were completed in a double-walled sound attenuating booth.

2.4 | Acoustic pitch change detection task

In the Active Listening portion of the pitch change detection task, participants were presented with 240 sequences of five repeated tones synthesized to sound like a piano. Each tone was 100 ms long with 10 ms onset and offset ramps and was presented at ∼70 dB SPL. There was a 400 ms silent interval from offset to onset of each tone and 2000 ms from the end of one sequence to the start of the next sequence. The Standard tone was 1047 Hz. On half the trials, the fourth tone (i.e. deviant) was shifted upward or downward by 25 cents (1062 or 1032 Hz) or 200 cents (1175 Hz or 933 Hz). All other tones were standard. The order of the trials was randomized. After each trial, participants were told to press a button on a keyboard labelled 'different' whenever they heard a sequence where the five tones were not identical; participants pressed a button labelled 'same' when they heard a sequence where all five tones were identical. This technique ensures that the inter-stimulus interval between standard and deviant tones was similar in both the active and passive (see following text) listening conditions so that the resulting MMN is comparable (Näätänen et al., 2007). Moreover, this approach makes the task comparable with the musical pitch detection task (see following text), where participants listened to a complete melody before responding if one of the notes was in- or out-of-key. Participants were given unlimited time to respond, but were instructed to respond as quickly as they could, while prioritizing accuracy. No feedback about participants' responses was given. This task lasted about 15 min, and participants could take a short break halfway through.

In the Passive Listening portion of the pitch change detection task, participants watched a silent movie with subtitles and were asked to ignore the auditory stimulation. The stimuli were identical to those used during Active Listening, but tones were presented continuously with an inter-stimulus interval of 400 ms, and not in groups of five tones. A total of 3040 stimuli were presented. The standard stimulus was presented 2736 times, and deviant tones were presented 304 times, yielding a 10% probability of a deviant. Each of the four deviant types (25-cent upward, 25-cent downward, 200-cent upward and 200-cent downward) were presented 76 times each. The duration and rise/fall times for the oddball tones was identical to the standard.

2.5 | Musical pitch detection task

Participants were presented with 40 novel melodies constructed from the Western major scale and saved as a MIDI file. All melodies were four bars long and were rendered using a synthesized piano tone and a synthesized guitar tone, yielding a total of 80 melodies. The RMS amplitude of each note was equated. On average, melodies had 10.3 notes (range: 7–15) and lasted 5.4 s (range: 2.8–12). They were randomly mixed with the same melodies in which 80 target tones were played out-of-key (±100 cents, one semitone; OK) and 80 target tones that were out-of-tune (±50 cents, ½ semitone; OT). The target tone (OT, OK or in-tune [IT]) was always on the first beat of the third bar and was always 500 ms long. All melodies were presented at 70 dB SPL. The melodies were the same as the melodies from previous studies (Peretz et al., 2009; Zendel et al., 2015; Zendel & Alexander, 2020). At the end of each melody, participants were asked if they heard a 'wrong' note. After each melody, participants could respond, 'wrong note', or 'no wrong note' by pressing a button on a computer keyboard. Participants were given unlimited time to respond, but were instructed to respond as quickly as they could, while prioritizing accuracy. There were 12 practice trials that included performance feedback. No feedback was provided for the experimental trials.

2.6 | EEG acquisition and analysis

Neuroelectric brain activity was recorded with Biosemi ActiveTwo system (BioSemi) from 70 electrodes at a sampling rate of 1024 Hz, with a high-pass filter set at 0.1 Hz.

Prototypical eye blinks and eye movements were extracted from the continuous EEG. A principal component analysis of these prototypical eye blinks and movements provided a set of components that best explained these ocular artefacts. These components were then decomposed into a linear combination along with topographical components that reflected brain activity. This linear combination allowed the scalp projections of the artefact components to be subtracted from the experimental ERPs to minimize ocular contamination, due to eye blinks, for each individual (Berg & Scherg, 1994).

Continuous EEG was averaged into ERPs using Brain Electrical Source Analysis (BESA; Version 6.1). ERPs were averaged to the onset of the target tone, and the analysis epoch included 100 ms of pre-stimulus activity and 1000 ms of post-stimulus activity. ERPs were re-referenced at the mastoids and filtered from 0.1 to 30 Hz. The ERP analysis was done in two steps. First, difference waves (standard/in-key − deviant/out-of-key/out-of-tune) were calculated. The peak latency of the MMN was quantified separately for active and passive listening over a montage of nine fronto-central electrodes (F1, Fz, F2, FC1, FCz, FC2, C1, Cz, C2) from 100 to 350 ms post-stimulus onset. The peak latency of the P300 and P600 was quantified over nine central parietal electrodes (CP1, CPz, CP2, P1, Pz, P2, PO3, POz, PO4) from 200 to 800 ms post stimulus onset for the P300 and from 400 to 800 ms post-stimulus onset for the P600. The peak latency of the ERAN was quantified over 16 fronto-right electrodes (AF4, AF8, AFz, Fz, F2, F4, F6, F8, FCz, FC2, FC4, FC6, Cz, C2, C4, C6) from 100 to 400 ms. These montages were chosen so data could be compared with previous studies that have used similar paradigms (Brattico et al., 2006; Lagrois et al., 2018; Peretz et al., 2009; Vuvan et al., 2018; Zendel & Alexander, 2020; Zendel et al., 2015). The epochs were chosen based on a visual approximation of the minimum amplitude before and after the peak of interest to ensure the peak picking procedure selected the correct peak, and not the peak of a different wave that occurred before or after the peak of interest. No effects of Group (Poor PP vs. Normal PP) were observed for latency (see following text). Accordingly, mean amplitudes were calculated for the ±50 ms of the peak latency for each ERP (i.e. standard and deviant), and this window was the same for both groups. Group effects were then quantified by examining differences in amplitude when the Tone was standard/in-key compared with when the Tone was a deviant/out-of-key/out-of-tune and if those differences interacted with Group (PPP vs. NPP). Accordingly, main effects of Tone are indicative of the MMN/ERAN/P300/P600, whereas Tone × Group interactions are indicative of group differences in the MMN/ERAN/P300/P600.

3 | RESULTS

3.1 | Behavioural data

Accuracy for all tasks was calculated as percentage Hits minus percentage False Alarms (H-FA%). For the pitch change detection task, a hit was when a participant correctly identified a deviant tone, and a false alarm was when they reported hearing a deviant tone when there was none. For the melody task, a hit was when a

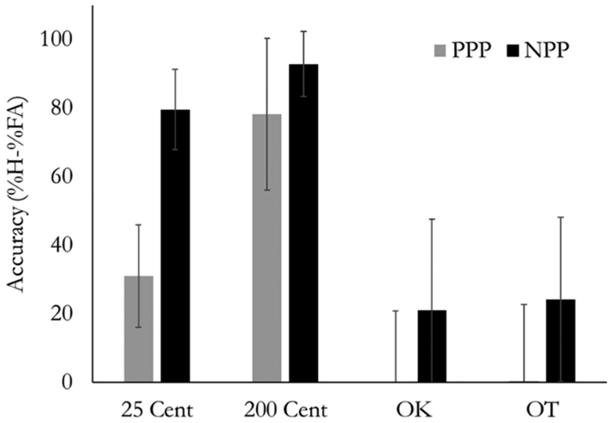

FIGURE 1 Accuracy on the pitch change detection task and melody task. For the pitch change detection task, accuracy was calculated as hits (correct identification of a pitch change) minus false alarms (identification of a pitch change when none was present). Poor pitch processors (PPP) performed worse than Normal pitch processors (NPP) when the pitch change was 25 cents ($p < 0.001$), but not when it was 200 cents ($p = 0.09$). For the melody task, accuracy was calculated as hits (correct identification of a wrong note) minus false alarms (identification of a wrong note when none was present). Normal pitch processors (NPP) were better at detecting out-of-key (OK) and out-of-tune (OT) notes compared to PPP ($p = 0.055$)

participant correctly identified that they heard a wrong note (out-of-key or out-of-tune) in the melody, and false alarm was when a participant reported hearing a wrong note, when all the notes were in-key. Data from the Pitch change detection task was analysed using a 2 (Deviant: 25-cent, 200-cent) × 2 (group: PPP, NPP) mixed designed ANOVA. Data from the Melody task was analysed using a 2 (Note type: out-of-key, out-of-tune) × 2 (Group, PPP, NPP) mixed design ANOVA. Results can be seen in Figure 1.

3.2 | Acoustic pitch change detection task

Accuracy was higher for the 200-cent deviant compared with the 25-cent deviant, $F(1,16) = 98.16$, $p < 0.001$, $\eta^2 = 0.86$. Additionally, Normal PPs had greater accuracy compared with Poor PPs, $F(1,16) = 23.25$, $p < 0.001$, $\eta^2 = 0.59$. The difference in accuracy between the groups was larger for the 25-cent deviant compared with the 200-cent deviant, as the Group-by-Deviant interaction was significant, $F(1,16) = 30.64$, $p < 0.001$, $\eta^2 = 0.66$. Follow-up analyses from this interaction revealed that NPPs were better able to detect a 25 deviant compared with the PPPs ($p < 0.001$), whereas there was no difference between the groups for the 200-cent deviant ($p = 0.09$). Although the NPP performed better than the PPP, both groups were able to detect the for the 25-cent deviant above chance levels (NPP: $t(8) = 22.36$, $p < 0.001$; PPP: $t(8) = 6.25$, $p < 0.001$). Chance performance was when hits minus false alarms was 0.

3.3 | Musical pitch detection task

Overall, both out-of-key and out-of-tune notes were detected at similar rates, as the main effect of Note type was not significant, $F(1,16) = 1.14$, $p = 0.30$, $\eta^2 = 0.07$. Normal PPs were better at detecting a wrong note compared with Poor PPs, $F(1,16) = 4.29$, $p = 0.055$, $\eta^2 = 0.21$. NPP were equally better than PPP at detecting both out-of-key and out-of-tune notes as the Group-by-Note type interaction was not significant, $F(1,16) = 0.33$, $p = 0.57$, $\eta^2 = 0.02$. Importantly, the NPP were able to perform this task above chance for both the out-of-key deviant, $t(8) = 2.40$, $p = 0.04$, and the out-of-tune deviant $t(8) = 3.04$, $p = 0.02$; however, three individuals within this group performed at or below chance (see Figure 8). As a group, the PPP were not able to perform this task above chance, $p > 0.9$ for both tasks; however, three individuals were able to perform this task above chance (see Figure 8). Chance performance was when hits minus false alarms was 0.

3.4 | ERP data

Each deviant was analysed separately (i.e. 25- and 200-cent in acoustic pitch change and out-of-tune and out-of-key in musical pitch change) because the analysis involves a comparison with the standard tone. If they were analysed in the same analysis, the EEG data from the standard tone would be included in the analysis twice. This is the case for both difference waves used to calculate the peak latency, where the deviant was subtracted from the standard, and in the evoked responses to each stimulus used to calculate the mean amplitude, where the deviant ERPs were included in the model.

3.5 | MMN passive listening: Peak latency (acoustic pitch change)

For the 25-cent and 200-cent deviant tones, peak latency and amplitude was extracted as the largest negative peak in the difference wave from 100 to 350 ms.

Peak latency of the MMN evoked by a 25-cent deviant was similar for both PPP and NPP, $F(1,16) = 1.74$, $p = 0.21$, $\eta^2 = 0.1$. Overall, the MMN peaked at 292 ms.

Peak latency of the MMN evoked by a 200-cent deviant was similar for both PPP and NPP, $F(1,16) = 0.46$, $p = 0.49$, $\eta^2 = 0.03$. Overall, the MMN peaked at 247 ms.

3.6 | MMN passive listening: Mean amplitude (acoustic pitch change)

The mean amplitude window was chosen as ±50 ms from the peak identified in the previous analysis. Mean amplitude for the MMN evoked by a 25-cent deviant was extracted from 242 to 342 ms (peak = 292 ms) for both Tones (Standard, 25-cent deviant). There was a main effect of Tone, $F(1,16) = 10.12$, $p = 0.006$, $\eta^2 = 0.39$, with 25 Deviants evoking a more negative response than the Standard (i.e. the MMN; Figure 2). Importantly, the Tone-by-Group interaction was not significant, $F(1,16) = 0.94$, $p = 0.35$, $\eta^2 = 0.06$, indicating that the MMN evoked by a 25-cent deviant (i.e. the statistical difference between the standard and 25-cent deviant) was similar in both groups.

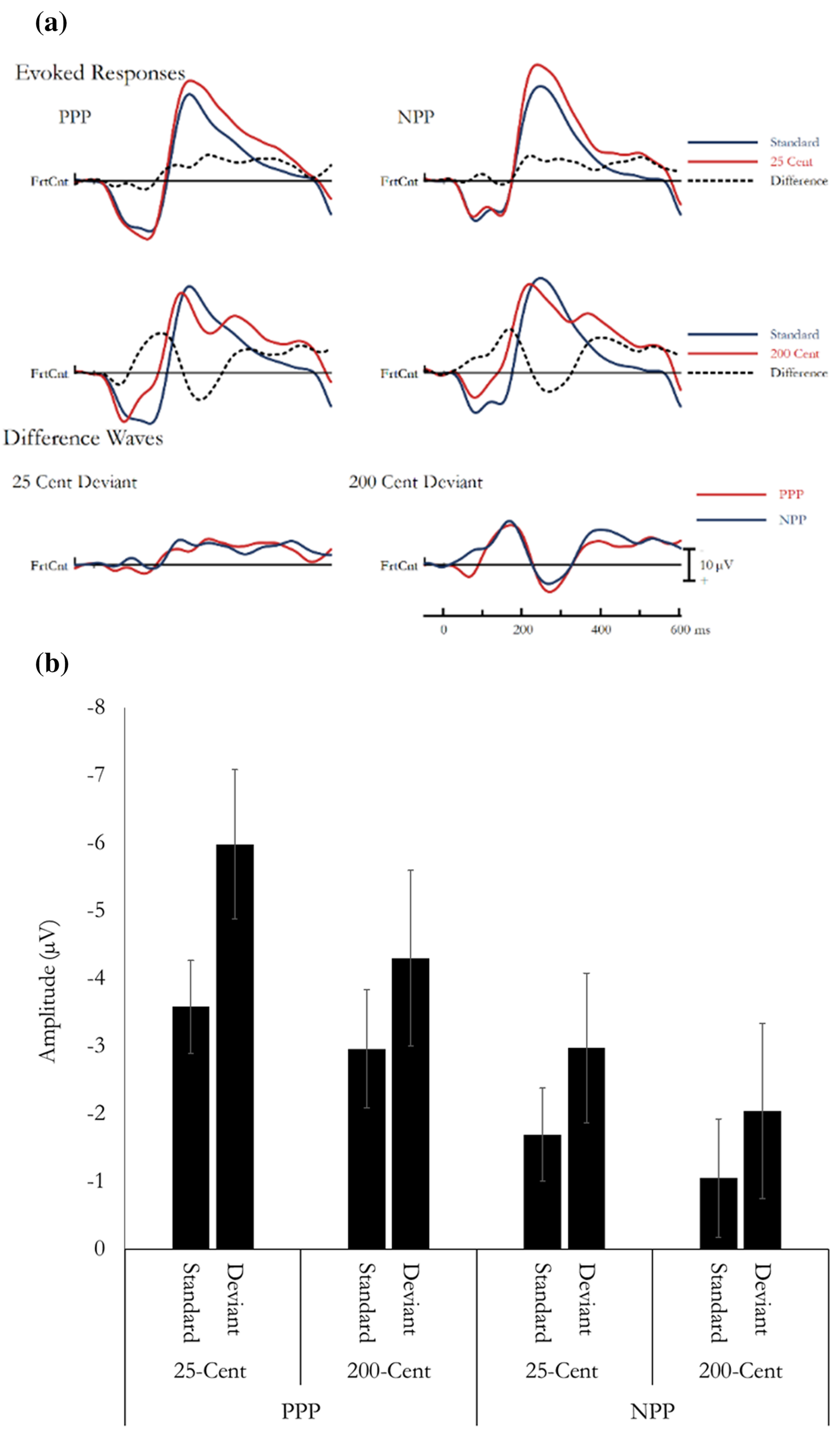

FIGURE 2 Mismatch negativity (MMN) amplitude (passive listening). (a). On the top row and middle rows are ERP plots for the 25-cent and 200-cent deviants, respectively, with PPP on the left and NPP on the right. Plots are averages of the nine fronto-central electrode montage used in the analysis (F1, Fz, F2, FC1, FCz, FC2, C1, Cz, C2). Evoked responses to the standard stimulus are in blue, and the deviant stimulus are in red. The difference wave (deviant minus standard) is presented in a dotted line. On the bottom row, the difference waves for both groups are presented on the same plot, with the 25-cent deviant on the left and the 200-cent deviant on the right. (b). Amplitude averaged across nine fronto-central electrodes from 242 to 342 ms for the 25-cent deviant and from 197 to 297 ms for the 200-cent deviant. Amplitude of deviant tones was more negative than amplitude for standard tones, although this difference was only significant for the 25-cent deviant ($p = 0.006$, 0.12). Critically, no differences between groups was observed for the 25- and 200-cent deviants ($p = 0.35$ and 0.81)

Mean amplitude of the MMN evoked by a 200-cent deviant was extracted from 197 to 297 ms (peak 247 ms) for both Tones (Standard, 200-cent deviant). The response evoked by the 200-cent deviant tone was more negative than the response evoked by the Standard Tone (i.e. the MMN; Figure 2); however, this difference failed to reach significance, $F(1,16) = 2.73$, $p = 0.12$, $\eta^2 = 0.15$. Importantly, the Tone-by-Group interaction was not significant, $F(1,16) = 0.06$, $p = 0.81$, $\eta^2 = 0.004$, indicating that the MMN evoked by a 200-cent deviant was similar in both groups.

3.7 | MMN active listening: Peak latency (acoustic pitch change detection)

For the 25-cent and 200-cent deviant tones, peak latency and amplitude was extracted as the largest negative peak in the difference wave from 100 to 350 ms.

Peak latency of the MMN evoked by a 25-cent deviant was similar for both PPP and NPP, $F(1,16) = 0.22$, $p = 0.64$, $\eta^2 = 0.01$. Overall, the MMN peaked at 240 ms. Peak latency of the MMN evoked by a 200-cent deviant was similar for both PPP and NPP, $F(1, 16) = 0.61$, $p = 0.45$, $\eta^2 = 0.04$. Overall, the MMN peaked at 168 ms.

3.8 | MMN active listening: Mean amplitude (acoustic pitch change detection)

The mean amplitude window was chosen as ±50 ms from the peak identified in the previous analysis. Mean amplitude for the MMN evoked by a 25-cent deviant was extracted from 190 to 290 ms (peak = 240 ms) for both Tones (Standard, 25-cent deviant). There was a main effect of Tone, $F(1,16) = 20.91$, $p < 0.001$, $\eta^2 = 0.57$, with 25-cent deviants evoking a more negative response than the Standard (i.e. the MMN; Figure 3). Importantly, the Tone-by-Group interaction was not significant, $F(1,16) = 0.68$, $p = 0.42$, $\eta^2 = 0.04$, indicating that the MMN evoked by a 25-cent deviant was similar in both groups.

Mean amplitude of the MMN evoked by a 200-cent deviant was extracted from 118 to 218 ms (peak = 168 ms) for both Tones (Standard, 200-cent deviant). There was a main effect of Tone, $F(1,16) = 35.85$, $p < 0.001$, $\eta^2 = 0.69$, with 200 Deviants evoking a more negative response than the Standard (i.e. the MMN; Figure 3). Importantly, the Tone-by-Group interaction was not significant, $F(1,16) = 0.71$, $p = 0.41$, $\eta^2 = 0.04$, indicating that the MMN evoked by a 200-cent deviant was similar in both groups.

3.9 | P300: Peak latency (acoustic pitch change detection)

For the 25-cent and 200-cent deviant tones, peak latency and amplitude was extracted as the largest negative peak in the difference wave from 200 to 800 ms.

Peak latency of the P300 evoked by a 25-cent deviant was similar for both PPP and NPP, $F(1,16) = 0.78$, $p = 0.39$, $\eta^2 = 0.05$. Overall, the P300 peaked at 603 ms. Peak latency of the P300 evoked by a 200-cent deviant was similar for both PPP and NPP, $F(1,16) = 0.03$, $p = 0.87$, $\eta^2 = 0.002$. Overall, the P300 peaked at 429 ms.

3.10 | P300 mean amplitude (acoustic pitch change detection)

Mean amplitude for the P300 evoked by a 25-cent deviant was extracted from 553 to 653 ms (peak = 603 ms) for both Tones (Standard, 25-cent deviant). There was a main effect of Tone, $F(1,16) = 16.92$, $p = 0.001$, $\eta^2 = 0.51$, with 25 Deviants evoking a more positive response than the Standard (i.e. the P300; Figure 4). Importantly, this effect was qualified by a significant interaction between Tone and Group, $F(1,16) = 12.66$, $p = 0.003$, $\eta^2 = 0.44$, indicating that the amplitude difference between the standard and 25-cent deviant tones was larger in the NPP compared with the PPP. As can be seen in Figure 4, there is almost no difference in the standard and 25-cent deviant ERPs in the PPP group.

Mean amplitude of the P300 evoked by a 200-cent deviant was extracted from 379 to 479 ms (peak = 429 ms) for both Tones (Standard, 200-cent deviant). There was a main effect of Tone, $F(1,16) = 48.16$, $p < 0.001$, $\eta^2 = 0.75$, with 200 Deviants evoking a more positive response than the Standard (i.e. the P300; Figure 4). Importantly, the Tone-by-Group interaction was not significant, $F(1,16) = 0.17$, $p = 0.69$, $\eta^2 = 0.01$, indicating that the P300 evoked by a 200-cent deviant was similar in both groups.

3.11 | ERAN peak latency (musical pitch detection)

For out-of-key and out-of-tune notes in melodies, the peak latency and amplitude of the ERAN was extracted as the largest negative peak in the difference wave from 100 to 400 ms.

Peak latency of the ERAN evoked by an out-of-key note was similar for both PPP and NPP, $F(1,16) = 0.39$, $p = 0.54$, $\eta^2 = 0.02$. Overall, the ERAN evoked by an out-of-key note peaked at 266 ms. Peak latency of the ERAN

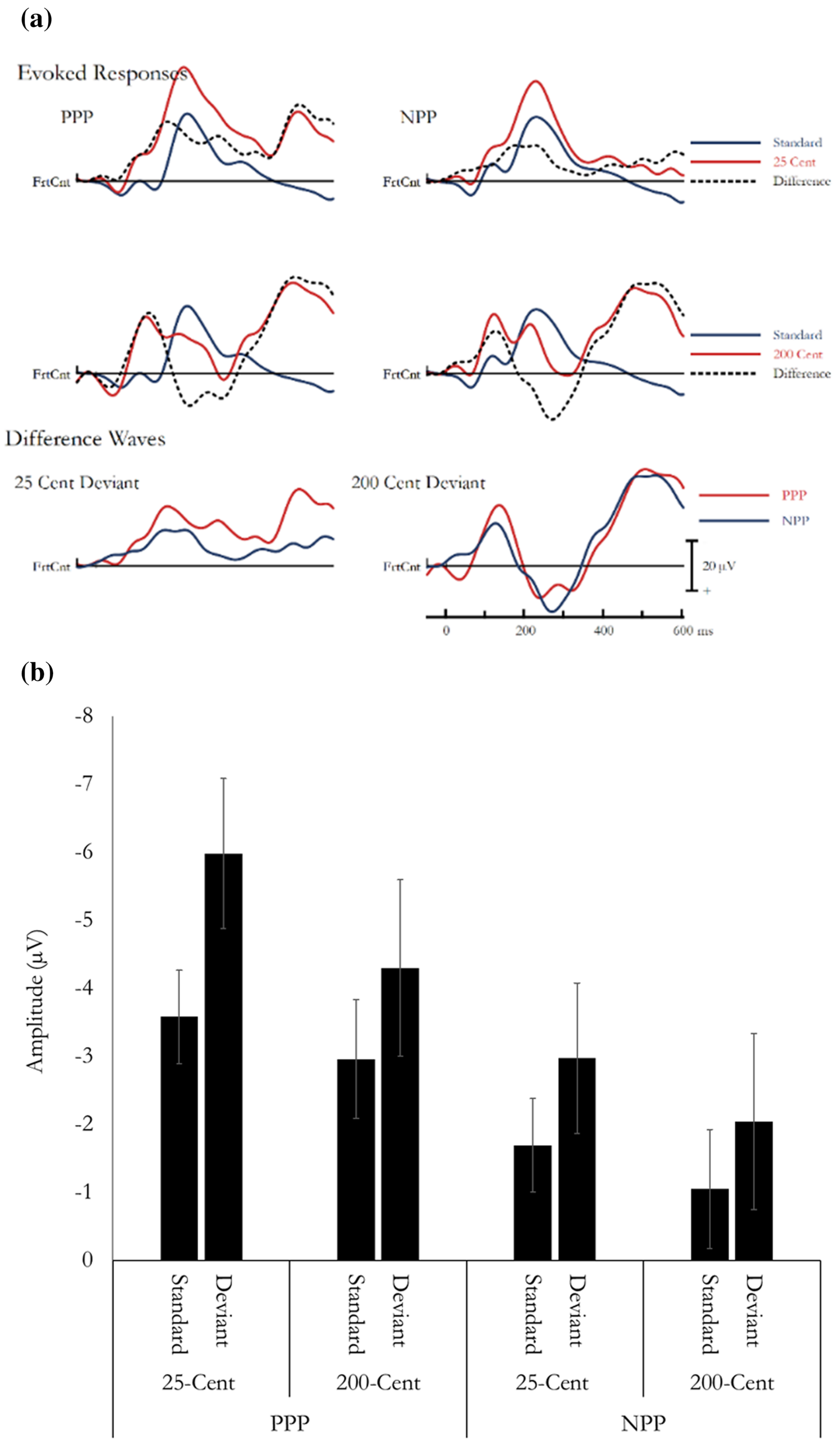

FIGURE 3 Mismatch negativity (MMN) amplitude (active listening). (a). On the top row and middle rows are ERP plots for the 25-cent and 200-cent deviants, respectively, with PPP on the left and NPP on the right. Plots are averages of the nine fronto-central electrode montage used in the analysis (F1, Fz, F2, FC1, FCz, FC2, C1, Cz, C2). Evoked responses to the standard stimulus are in blue, and the deviant stimulus are in red. The difference wave (deviant minus standard) is presented in a dotted line. On the bottom row, the difference waves for both groups are presented on the same plot, with the 25-cent deviant on the left and the 200-cent deviant on the right. (b). Amplitude averaged across nine fronto-central electrodes from 190 to 290 ms for the 25-cent deviant and from 118 to 218 ms for the 200-cent deviant. Amplitude of deviant tones was more negative than amplitude for standard tones (25-cent: $p < 0.001$; 200-cent: $p < 0.001$), and no differences between groups was observed (25-cent: $p = 0.42$; 200-cent: $p = 0.41$)

evoked by an out-of-tune note was similar for both PPP and NPP, $F(1,16) = 2.35$, $p = 0.15$, $\eta^2 = 0.13$. Overall, the ERAN evoked by an out-of-tune note peaked at 274 ms.

3.12 | ERAN mean amplitude (musical pitch detection)

Mean amplitude for the ERAN evoked by an out-of-key note was extracted from 216 to 316 ms (peak = 266 ms) for both Note types (in-key, out-of-key). The response evoked by the out-of-key note was more negative than the response evoked by the in-key notes (i.e. the ERAN; Figure 5); however, this difference failed to reach significance, $F(1,16) = 4.01$, $p = 0.061$, $\eta^2 = 0.20$. Importantly, the Note type-by-Group interaction was not significant, $F(1,16) = 1.04$, $p = 0.32$, $\eta^2 = 0.06$, indicating that the ERAN evoked by an out-of-key note was similar in both groups.

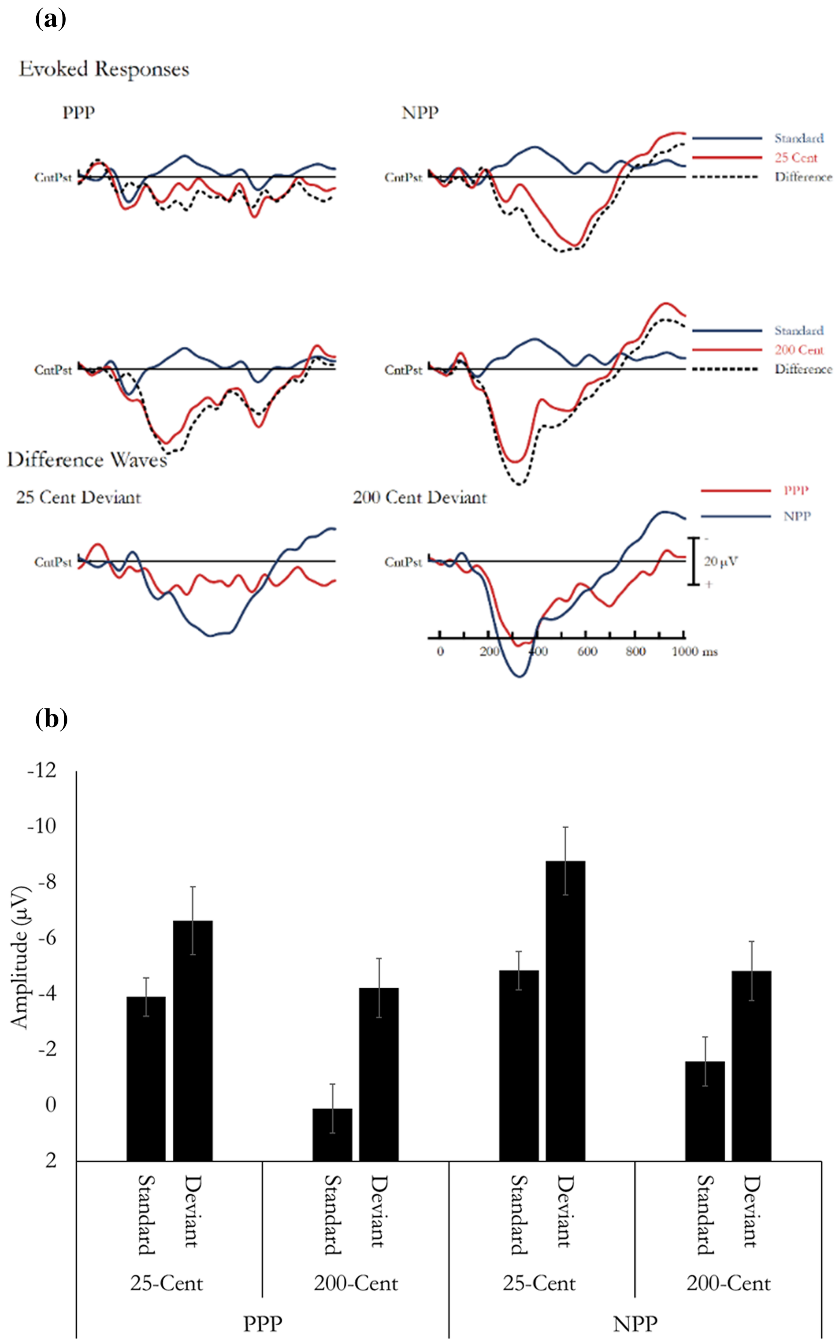

FIGURE 4 P300 amplitude. (a). On the top row and middle rows are ERP plots for the 25-cent and 200-cent deviants, respectively, with PPP on the left and NPP on the right. Plots are averages of the nine central parietal electrode montage used in the analysis (CP1, CPz, CP2, P1, Pz, P2, PO3, POz, PO4). Evoked responses to the standard stimulus are in blue, and the deviant stimulus are in red. The difference wave (deviant minus standard) is presented in a dotted line. On the bottom row, the difference waves for both groups are presented on the same plot, with the 25-cent deviant on the left and the 200-cent deviant on the right. (b). Amplitude averaged across nine central-parietal electrodes from 553 to 653 ms for the 25-cent deviant and from 379 to 479 ms for the 200-cent deviant. Amplitude of deviant tones was more negative than amplitude for standard tones ($p < 0.001$). The P300 evoked by a 25-cent deviant was smaller in PPP compared with NPP ($p = 0.003$)

Mean amplitude of the ERAN evoked by an out-of-tune note was extracted from 224 to 324 ms (peak = 274 ms) for both Note types (in-key, out-of-tune). There was a main effect of Note type, $F(1,16) = 10.38$, $p = 0.005$, $\eta^2 = 0.39$, with out-of-tune notes evoking a more negative response than in-tune notes (i.e. the ERAN; Figure 5). Importantly, the Note type-by-Group interaction was not significant, $F(1,16) = 0.93$, $p = 0.35$, $\eta^2 = 0.06$, indicating that the ERAN evoked by an out-of-tune note was similar in both groups.

3.13 | P600 peak latency (musical pitch detection)

For out-of-key and out-of-tune notes, the peak latency and amplitude of the P600 was extracted as the largest negative peak in the difference wave from 400 to 800 ms.

Peak latency of the P600 evoked by an out-of-key note was similar for both PPP and NPP, $F(1,16) = 0.65$, $p = 0.43$, $\eta^2 = 0.04$. Overall, the P600 evoked by an out-of-key note peaked at 611 ms. Peak latency of the P600 evoked by an out-of-tune note was similar for both PPP

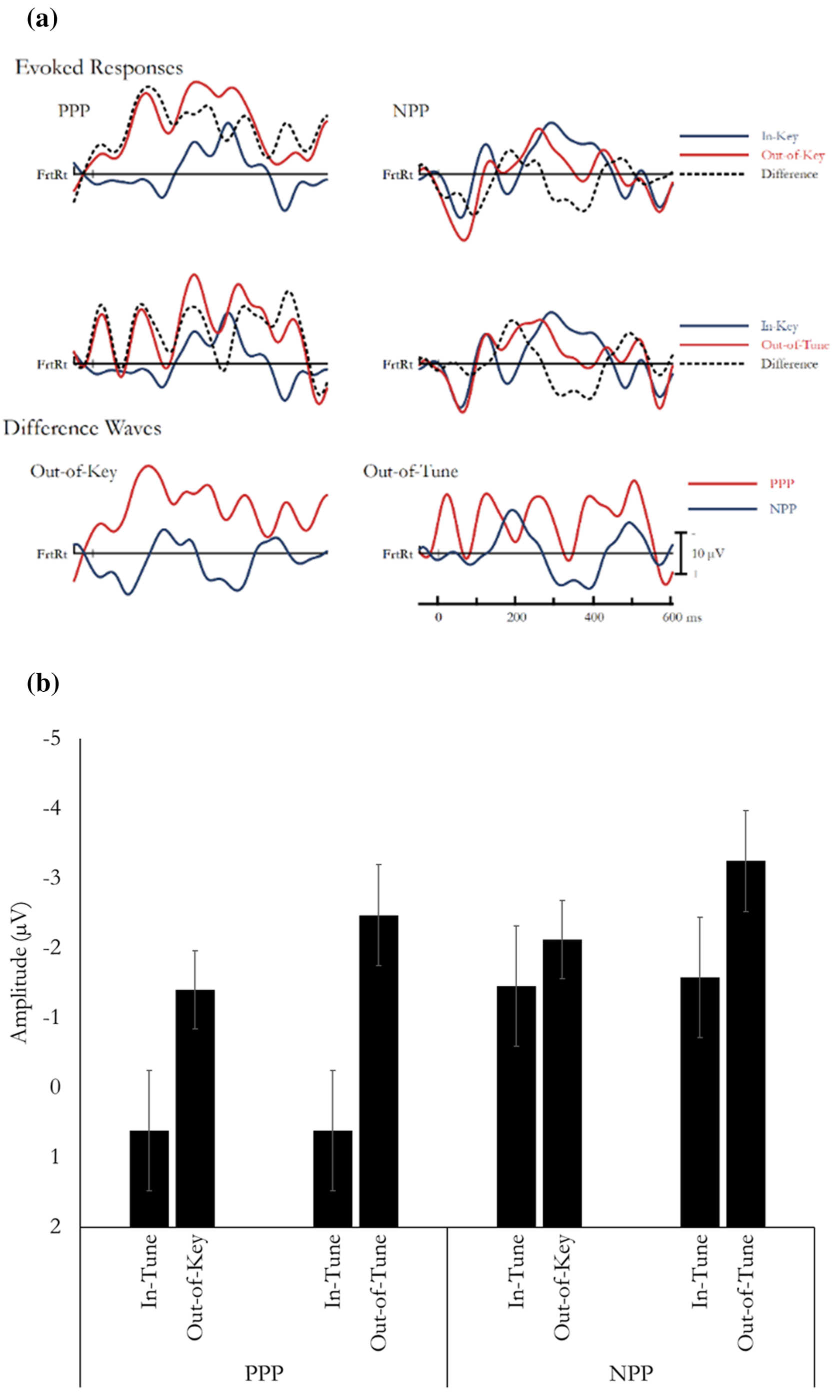

FIGURE 5 ERAN amplitude. (a). On the top row and middle rows are ERP plots for the in-tune (IT), out-of-key (OK), and out-of-tune (OT) notes, respectively, with PPP on the left and NPP on the right. Plots are averages of the 16 fronto-right electrode montage used in the analysis (AF4, AF8, AFz, Fz, F2, F4, F6, F8, FCz, FC2, FC4, FC6, Cz, C2, C4, C6). Evoked responses to the IK stimulus are in blue, and the OK/OT stimulus are in red. The difference wave (IK minus OK/OT) is presented in a dotted line. On the bottom row, the difference waves for both groups are presented on the same plot, with the OK note on the left and the OT on the right. (b). Amplitude averaged across 16 fronto-right electrodes from 216 to 316 ms for the OK note and from 224 to 324 ms for the OT note. Amplitude of OK/OT notes was more negative than amplitude for standard tones ($p = 0.061$ and 0.005, respectively), and no differences between groups were observed for the OK nor OT notes ($p = 0.32$ and 0.35, respectively)

and NPP, $F(1,16) = 0.18$, $p = 0.68$, $\eta^2 = 0.01$. Overall, the P600 evoked by an out-of-tune note peaked at 659 ms.

3.14 | P600 mean amplitude (musical pitch detection)

Mean amplitude for the P600 evoked by an out-of-key note was extracted from 561 to 661 ms (peak = 611 ms) for both Note types (in-key, out-of-key). The response evoked by the out-of-key note was more positive than the response evoked by the in-key notes (i.e. the P600; Figure 6); however, this difference failed to reach significance, $F(1,16) = 3.01$, $p = 0.10$, $\eta^2 = 0.16$. Importantly, this effect was qualified by a significant interaction between Note type and Group, $F(1,16) = 5.15$, $p = 0.037$, $\eta^2 = 0.24$, indicating that the P600 evoked by an out-of-key Note was larger in the NPP compared with the PPP. Figure 6 illustrates that this difference is because the P600 was absent in the PPP group.

Similarly, the mean amplitude of the P600 evoked by an out-of-tune note was extracted from 609 to 709 ms

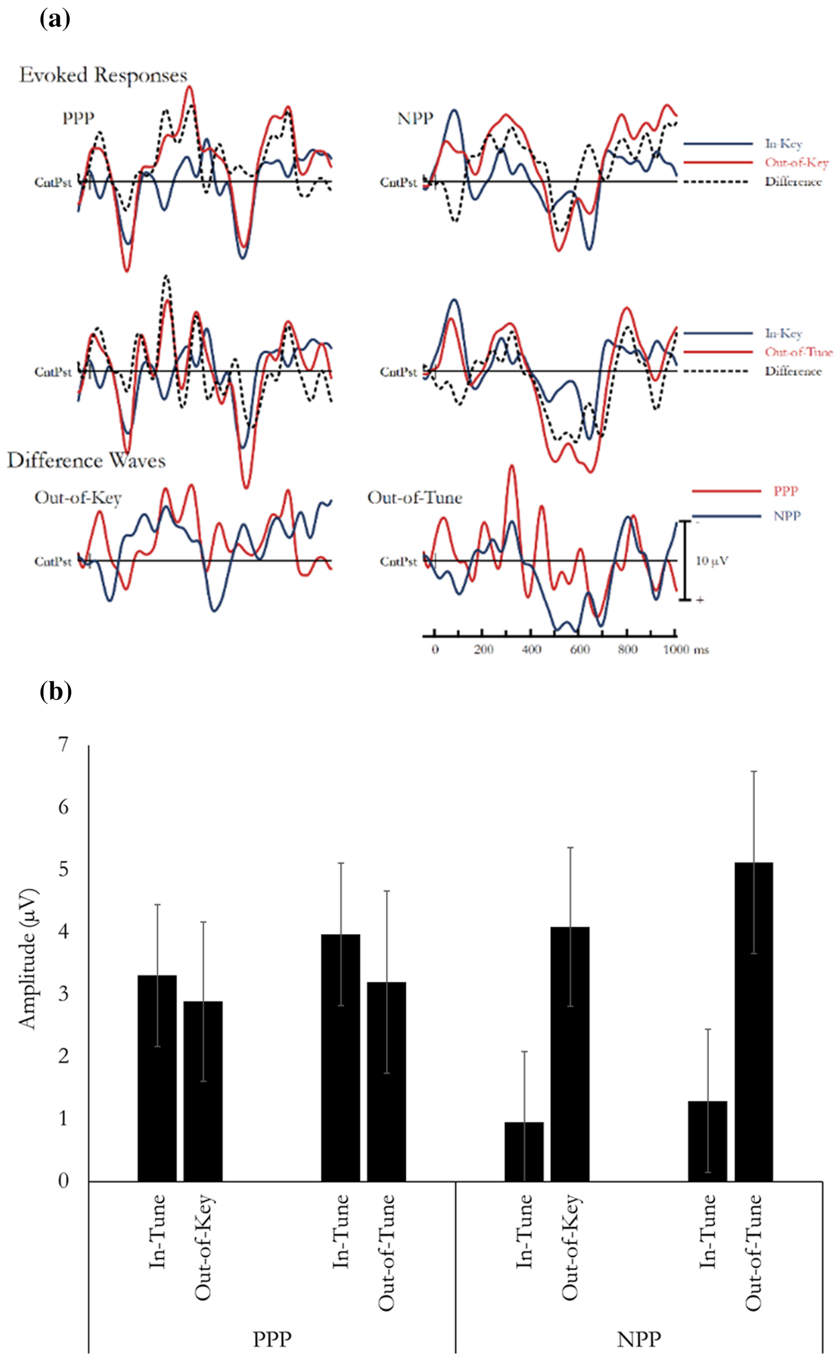

FIGURE 6 P600 amplitude. (a). On the top row and middle rows are ERP plots for the in-key (IK), out-of-key (OK), and out-of-tune (OT) notes, respectively, with PPP on the left and NPP on the right. Plots are averages of the nine central-parietal electrode montage used in the analysis (CP1, CPz, CP2, P1, Pz, P2, PO3, POz, PO4). Evoked responses to the IK stimulus are in blue, and the OK/OT stimulus are in red. The difference wave (IK minus OK/OT) is presented in a dotted line. On the bottom row, the difference waves for both groups are presented on the same plot, with the OK note on the left and the OT on the right. (b). Amplitude averaged across nine central parietal electrodes from 561 to 661 ms for the OK note and from 609 to 709 ms for the OT note. Amplitude of OK/OT notes was more positive than amplitude for standard tones, for the NPP, but not for the PPP ($p = 0.037$ and 0.011, respectively)

(peak = 659 ms) for both Note types (in-key, out-of-tune). The response evoked by the out-of-tune note was more positive than the response evoked by the in-key note (i.e. the P600; Figure 6); however, this difference failed to reach significance, $F(1,16) = 3.64$, $p = 0.07$, $\eta^2 = 0.19$. Importantly, this effect was qualified by a significant interaction between Note type and Group, $F(1,16) = 8.24$, $p = 0.011$, $\eta^2 = 0.34$, indicating that the P600 evoked by an out-of-tune note was larger in the NPP compared with the PPP. Figure 6 illustrates that this difference is because the P600 was absent in the PPP group.

3.15 | ERP-behaviour correlations

To examine the relationship between accuracy and brain activity, correlations were calculated between the amplitude of the MMN, P300, ERAN and P600, and the accuracy (H-FA%) during the same condition. MMN amplitude was not related to the ability to detect a 25-cent pitch oddball, $r(17) = -0.37$, $p = 0.13$, nor a 200-cent oddball, $r(17) = 0.32$, $p = 0.20$. The amplitude of the P300 predicted accuracy for both the 25-cent pitch deviant, $r(17) = 0.68$, $p = 0.002$, and for the 200-cent pitch deviant, $r(17) = 0.49$, $p = 0.04$ (Figure 7a,b). The amplitude of the ERAN was not related to the ability to detect an out-of-key note, $r(17) = 0.08$, $p = 0.77$, nor an out-of-tune note, $r(17) = 0.05$, $p = 0.85$. The amplitude of the P600 predicted accuracy for both the out-of-key note, $r(17) = 0.58$, $p = 0.012$, and for the out-of-tune note, $r(17) = 0.63$, $p = 0.006$ (Figure 7c,d). One interesting pattern to note here is that the P600 was usually small or non-existent (i.e. negative polarity) in Poor PPs even when performance was above chance (see Figure 7c,d).

3.16 | Relationship between acoustic and music pitch processing

To examine the relationship between the ability to detect small pitch changes and the ability to detect out-of-key or out-of-tune notes, correlations were calculated between the H-FA% for the 25-cent pitch change and H-FA% for the out-of-key and out-of-tune notes. Neither of these correlations were significant, $r(18) = 0.30$ and 0.23, $p > 0.05$; however, it should be noted that the Poor PP group could not reliably detect the 25-cent deviant, and only three members of this group could detect either the out-of-key or out-of-tune notes. Accordingly, we calculated the relationship between the ability to detect a small pitch change and the ability to detect wrong note separately in the Poor PP and the Normal PP groups. In the Normal PP, the relationship between the 25-cent H-FA% and the out-of-key/out-of-tune H-FA% were not significant, $r(8) = 0.13$ and 0.31, $p > 0.4$. Although neither of these relationships was statistically significant, there was a general positive trend for the Normal PP: as 25-cent H-FA% increased, so did H-FA% for wrong notes. For the Poor PP the relationship between 25-cent H-FA% and the out-of-key/out-of-tune HFA% was significant, $r(8) = -0.85$ and -0.85, $p = 0.003$ and 0.004; however, because none the Poor PPs could not reliably detect the 25-cent pitch change, this correlation is likely spurious and driven by the three Poor PPs who could perform the musical pitch detection task above chance (Figure 8).

3.17 | Relationship of the MBEA to acoustic and music pitch deviant detection

There is a long history of using the MBEA as a diagnostic tool to identify amusia. Here, we explored the relationship between the overall score on the MBEA and the ability to discriminate both pitch change and wrong notes. MBEA scores were correlated with both H-FA% for an out-of-tune note and an out-of-key note, $r(17) = 0.56$ and 0.59, $p = 0.02$ and 0.01. Interestingly, performance on the overall MBEA score was not related to H-FA% for a 25-cent nor 200-cent deviant ($p > 0.6$ for both).

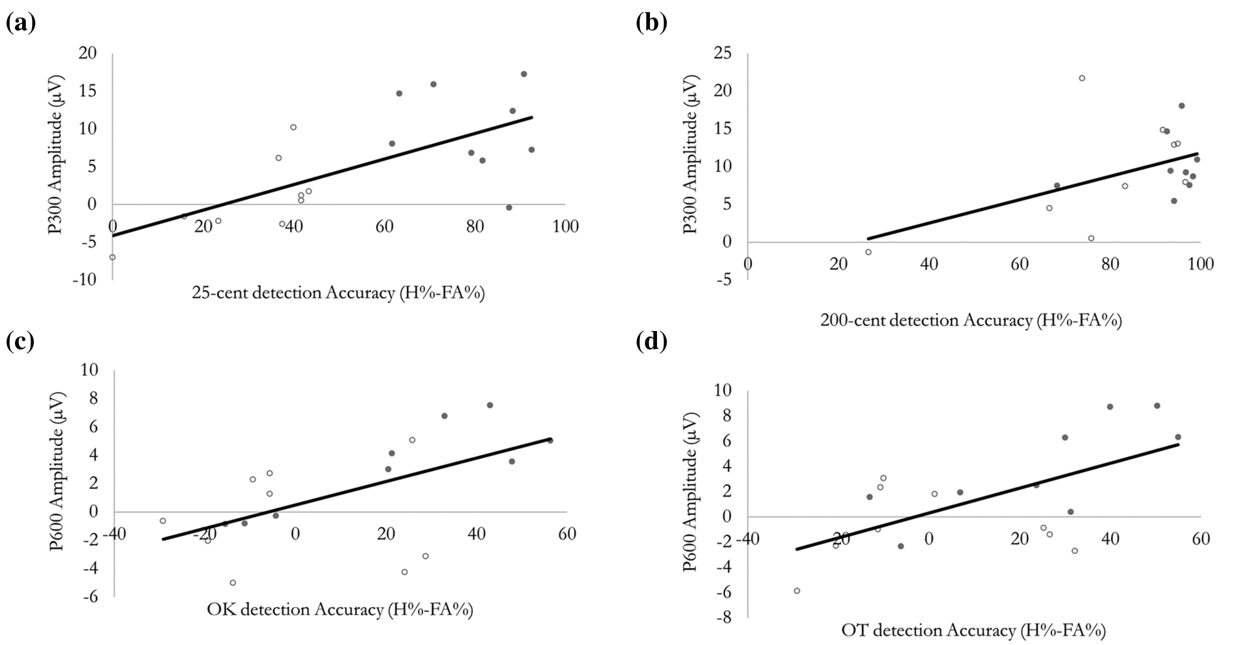

FIGURE 7 Brain–behaviour correlations. Filled circles are NPP, and empty circles are PPP. For all plots, ERP amplitude is averaged across the electrode montage, and epoch used in the analysis. (a) The relationship between P300 amplitude evoked by a 25-cent deviant and accuracy. (b) The relationship between P300 amplitude evoked by a 200-cent deviant and accuracy. (c) the relationship between P600 amplitude evoked by an out-of-key (OK) note and accuracy. (b) the relationship between P600 amplitude evoked by an out-of-tune (OT) note and accuracy

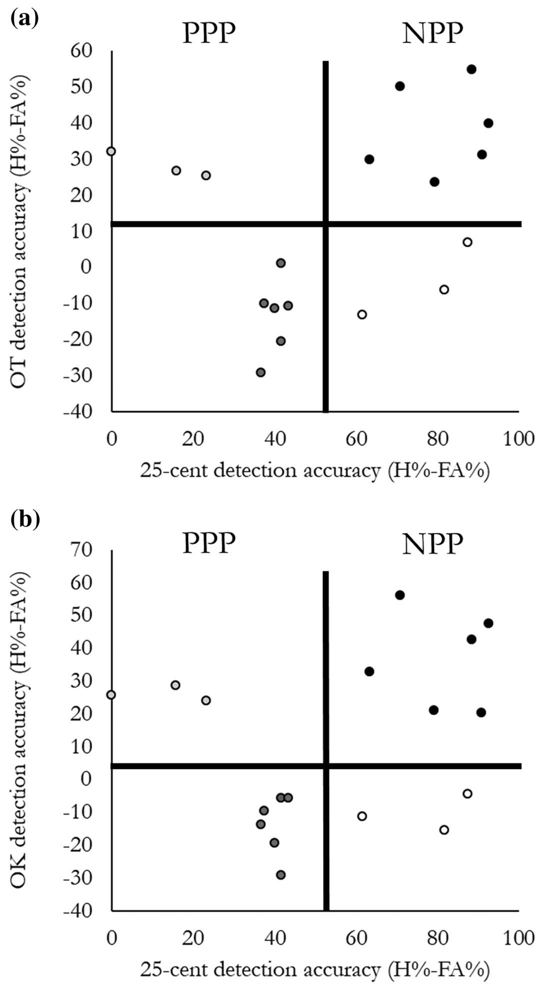

FIGURE 8 Pitch-tone correlations. (a) Hits%-false alarm% for detecting an out-of-key note as a function of the hits%-false alarm% for detecting a 25-cent pitch deviant. (b) Hits%-false alarm% for detecting an out-of-tune note as a function of the hits%-false alarm % for detecting a 25-cent pitch deviant. Both graphs are divided into quadrants to highlight the double dissociation between pitch processing and tonal processing. The upper right quadrant are NPPs who performed well on the tonal processing tasks (black). The lower right quadrant are NPPs who performed poorly on the tonal processing tasks (white). The upper left quadrant are PPPs who performed well on the tonal processing tasks (light grey). The lower left quadrant are PPPs who performed poorly on the tonal processing tasks

4 | DISCUSSION

Overall, adolescents with poor pitch processing abilities (Poor PPs) have a similar neurophysiological profile as adults with amusia. Across all conditions, early electrical brain responses to acoustical and musical pitch deviants (MMN or ERAN) were similar in Poor PPs compared with Normal Pitch Processors (Normal PPs). Late positivities associated with detection of acoustic or musical pitch deviants (P300 or P600) were absent, or attenuated in Poor PPs, but present in the Normal PPs when they could perform the task above chance. The amplitude of the late positivities (i.e. P300 or P600) predicted task performance, whereas the early ERP responses (MMN or ERAN) were unrelated to task performance. This neurophysiological profile matches the adult amusic neurophysiological profile that has been observed in multiple studies (see Peretz, 2016). Given that the groups were split based on their acoustic pitch discrimination abilities, it was not surprising that the Poor PPs could not reliably detect a 25-cent pitch change, whereas the Normal PPs could reliably detect this difference. Interestingly, the detection of a musical pitch deviant was not only difficult for the Poor PPs. About one-third of the Normal PPs performed at chance on this task. Even more interesting is that about one-third of the Poor PPs performed above chance and within the same range as the Normal PPs. This pattern of results is suggestive of a double dissociation between acoustic and music pitch discrimination.

The overall poor ability of Normal PPs to detect a melodic deviant came as a surprise. Previous work using the same melodies and scoring technique in adults have reported hits minus false alarms accuracy between 35% and 60% for out-of-tune notes and 35% and 55% for out-of-key notes (Lagrois et al., 2018; Vuvan et al., 2018; Zendel et al., 2015; Zendel & Alexander, 2020). One study explored developmental changes in older adults and found no difference between older and younger adults for the out-of-tune note but that older adults were more accurate at detecting out-of-key notes compared with younger adults (Lagrois et al., 2018). This overall pattern, that adolescents are worse than young adults at detecting out-of-key notes and that older adults are better than younger adults at detecting out-of-key notes (Lagrois et al., 2018), suggests that the ability to detect out-of-key notes improves throughout life. This pattern of results could be caused by accumulating experience and engagement with music. Alternatively, it is possible that detecting a musical deviant is a metacognitive task that requires conscious awareness of the tonal hierarchy and is therefore more challenging for young adolescents to understand compared with adults. With music education programmes being cut from public schools for the current cohort of adolescents, it is possible that adolescents can detect melodic deviants, but have difficulty categorizing them as being 'wrong'. An alternative possible cohort effect is that younger people may have more varied musical exposure than older adults, and thus have a more flexible sense of tonal structure. New tonal structures can be learned rapidly through passive exposure (Loui et al., 2010), and altered feedback during a tonal perception task can alter the perception of the Western tonal hierarchy in Western enculturated listeners (Vuvan et al., 2018). Accordingly, the perception of tonal structure is modifiable based on exposure to music. In the past decade, the Internet has made it easy for Western listeners to listen to music from a variety of cultures and styles, many of which would have been difficult to hear for members of older generations who were limited to what was broadcast on the radio, available at the local record store, or performed by local or touring musicians. Moreover, previous work has reported that older adults are less interested in new music and that older people tend to prefer pieces of music they liked when they were adolescents or young adults (Lamont et al., 2021). This suggests that older adults are less likely than younger adults to seek out new or unusual music online. It is therefore possible that younger individuals are listening to less Western music because of the variety of music available online and thus do not necessarily perceive some tonal violations as being explicitly wrong. More research is needed that compares cohort effects to developmental effects in order to better understand what causes the differences between age groups on the ability to detect out-of-key notes.

A novel and interesting aspect of the present study consisted in comparing the ability to detect a small (25-cent) acoustic pitch deviant and the ability to detect an out-of-key or out-of-tune note in a melody in the same adolescent participants. Contrary to expectations, a deficit in fine-grained pitch processing does not compromise the ability to detect a musical violation, and vice versa. As can be seen in Figure 8, there is evidence of a double dissociation. Three Poor PPs in the acoustic task were normal at detecting a musical pitch violation. Conversely, there were three Normal PPs, with good acoustic pitch detection abilities, who failed on the musical pitch violation task (Figure 8a,b). The presence of these six cases out of 18 suggest that acoustic and musical pitch processing are separable components during development. This proposal is consistent with previous work that has shown that there are some adults with significant music processing deficits who fall within the normal range of acoustic pitch discrimination (Liu et al., 2010; Vuvan et al., 2015). Vuvan et al. (2015) reported that in a database of 106 adults with pitch and/or music processing deficits, there were nine individuals with normal acoustic pitch discrimination abilities but poor melodic pitch discrimination abilities and that there were 17 individuals with normal melodic discrimination abilities, but poor acoustic discrimination abilities. One possible explanation for the double dissociation is that acoustic pitch discrimination and music pitch discrimination develop independently of each other (Vuvan et al., 2015). It is possible that the development of acoustic pitch discrimination was delayed in some individuals past the sensitive period for musical pitch discrimination abilities, which would impact early musical development (Habib & Besson, 2009). After this sensitive period, acoustic pitch processing developed normally, but because of the delay, left a lasting impact on musical pitch processing. For the other group of individuals that have impaired acoustic pitch processing, but normal musical pitch processing, Vuvan et al. (2015) suggest that this may be due to age-related changes in the auditory system that impact pitch processing and are overcome in musical situations by enhanced top-down control. The current data suggest this is unlikely, as we observed this pattern in adolescent participants. Rather, acoustic and musical pitch processing may well emerge independently. Support for this proposal comes from a neuroimaging study that revealed activation in the right inferior parietal lobule during tasks that required detection of a melodic deviant compared with tasks that required detection of a pitch deviant, suggesting a neural dissociation between acoustic and musical pitch discrimination (Royal et al., 2016). This overall pattern of results suggests that acoustic pitch and musical pitch processing deficits are independent but often co-occur.

The hypothesis for this study was that adolescents with poor pitch processing abilities would also have poor musical processing abilities and that the pitch processing deficit seen in amusia was the cause of poor musical pitch perception. The data from the current study suggest that musical and acoustic pitch processing deficits are independent from each other. One major limitation in the current study is the sample size. A replication of this pattern is needed to confirm the double dissociation between acoustic and music pitch processing in adolescents. Another issue is the noise in the baseline period of the ERPs in the music pitch detection task. This task required identifying a target note in a melody, which makes it challenging to have a silent interval before the target stimuli. Accordingly, the baseline interval is noisier for ERPs recorded during the music pitch detection task compared with the acoustic pitch detection task. With these caveats in mind, the overall pattern observed in the current study implies that an acoustic pitch discrimination task would not be a good way to identify potential cases of amusia in adolescence or earlier.

4.1 | Summary

Data from the current study support the idea that the ability to detect pitch and melodic deviants are separable processing components, suggesting that an acoustical pitch processing deficit is not necessarily associated with a music processing deficit. Despite the fact that the majority of cases show a relationship between the ability to detect a pitch deviant and a melodic deviant, the relationship is not systematic. The results suggest that using a pitch discrimination task to identify potential cases of amusia early in development will misdiagnose about one-third of children who exhibit an acoustic pitch processing deficit, but not a musical pitch processing deficit.

ACKNOWLEDGEMENTS

This research was supported by the Canada Research Chairs programme for both IP and BRZ, a CIHR fellowship to GMG and a CIHR project grant to IP.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

AUTHOR CONTRIBUTIONS

IP: Conceptualized and designed study, provided research materials, wrote manuscript; GMG: conceptualized and designed study; collected and analysed data; OD: analysed data, wrote manuscript; BRZ: analysed data, wrote manuscript.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

ORCID

Benjamin Rich Zendel https://orcid.org/0000-0003-2674-7682
Özgen Demirkaplan https://orcid.org/0000-0003-0880-2916

REFERENCES

Berg, P., & Scherg, M. (1994). A multiple source approach to the correction of eye artifacts. *Electroencephalography and Clinical Neurophysiology*, *90*(3), 229–241. https://doi.org/10.1016/0013-4694(94)90094-9

Besson, M., & Faita, F. (1995). An event-related potential (ERP) study of musical expectancy: Comparison of musicians with nonmusicians. *Journal of Experimental Psychology: Human Perception and Performance*, *21*(6), 1278–1296.

Bigand, E., & Poulin-Charronnat, B. (2006). Are we "experienced listeners"? A review of the musical capacities that do not depend on formal musical training. *Cognition*, *100*(1), 100–130. https://doi.org/10.1016/j.cognition.2005.11.007

Brattico, E., Tervaniemi, M., Näätänen, R., & Peretz, I. (2006). Musical scale properties are automatically processed in the human auditory cortex. *Brain Research*, *1117*(1), 162–174.

Couvignou, M., & Kolinsky, R. (2021). Comorbidity and cognitive overlap between developmental dyslexia and congenital amusia in children. *Neuropsychologia*, *155*, 107811.

Couvignou, M., Peretz, I., & Ramus, F. (2019). Comorbidity and cognitive overlap between developmental dyslexia and congenital amusia. *Cognitive Neuropsychology*, *36*(1–2), 1–17.

Cuddy, L. L., & Badertscher, B. (1987). Recovery of the tonal hierarchy: Some comparisons across age and levels of musical experience. *Perception & Psychophysics*, *41*(6), 609–620. https://doi.org/10.3758/BF03210493

Habib, M., & Besson, M. (2009). What do music training and musical experience teach us about brain plasticity? *Music Perception*, *26*(3), 279–285. https://doi.org/10.1525/mp.2009.26.3.279

Hyde, K. L., & Peretz, I. (2004). Brains that are out of tune but in time. *Psychological Science*, *15*(5), 356–360. https://doi.org/10.1111/j.0956-7976.2004.00683.x

Kishon-Rabin, L., Amir, O., Vexler, Y., & Zaltz, Y. (2001). Pitch discrimination: Are professional musicians better than non-musicians? *Journal of Basic and Clinical Physiology and Pharmacology*, *12*(2), 125–144. https://doi.org/10.1515/JBCPP.2001.12.2.125

Kløve, H. (1963). *Grooved pegboard*. Lafayette Instruments.

Korkman, M., Kirk, U., & Kemp, S. (2007). *NEPSY-II* (2nd ed.). Harcourt Assessment.

Krumhansl, C. L., & Kessler, E. J. (1982). Tracing the dynamic changes in perceived tonal organization in a spatial representation of musical keys. *Psychological Review*, *89*(4), 334.

Lamont, A., Hargreaves, D., Creech, A., Hodges, D. A., & Hallam, S. (2021). Musical preferences. In A. Creech, D. A. Hodges, & S. Hallam (Eds.), *Routledge international handbook of music psychology in education and the community* (pp. 131–145). Routledge.

Liu, F., Patel, A. D., Fourcin, A., & Stewart, L. (2010). Intonation processing in congenital amusia: Discrimination, identification and imitation. *Brain*, *133*(6), 1682–1693. https://doi.org/10.1093/brain/awq089

Loui, P., Wessel, D. L., & Kam, C. L. H. (2010). Humans rapidly learn grammatical structure in a new musical scale. *Music Perception*, *27*(5), 377–388. https://doi.org/10.1525/mp.2010.27.5.377

Micheyl, C., Delhommeau, K., Perrot, X., & Oxenham, A. J. (2006). Influence of musical and psychoacoustical training on pitch discrimination. *Hearing Research*, *219*(1–2), 36–47. https://doi.org/10.1016/j.heares.2006.05.004

Mignault Goulet, G., Moreau, P., Robitaille, N., & Peretz, I. (2012). Congenital amusia persists in the developing brain after daily music listening. *PLoS ONE*, *7*(5), e36860. https://doi.org/10.1371/journal.pone.0036860

Mishra, S. K., Renken, L., Hernandez, M., & Rodrigo, H. (2021). Auditory development of frequency discrimination at extended high frequencies. *Ear and Hearing*, *42*(3), 700–708. https://doi.org/10.1097/AUD.0000000000000972

Moore, D. R., Cowan, J. A., Riley, A., Edmondson-Jones, A. M., & Ferguson, M. A. (2011). Development of auditory processing in 6-to 11-yr-old children. *Ear and Hearing*, *32*(3), 269–285. https://doi.org/10.1097/AUD.0b013e318201c468

Moreau, P., Jolicœur, P., & Peretz, I. (2013). Pitch discrimination without awareness in congenital amusia: Evidence from event-related potentials. *Brain and Cognition*, *81*(3), 337–344. https://doi.org/10.1016/j.bandc.2013.01.004

Näätänen, R., Paavilainen, P., Rinne, T., & Alho, K. (2007). The mismatch negativity (MMN) in basic research of central auditory processing: A review. *Clinical Neurophysiology*, *118*(12), 2544–2590. https://doi.org/10.1016/j.clinph.2007.04.026

Nilsson, M., Soli, S. D., & Sullivan, J. A. (1994). Development of the hearing in noise test for the measurement of speech reception thresholds in quiet and in noise. *The Journal of the Acoustical Society of America*, *95*(2), 1085–1099. https://doi.org/10.1121/1.408469

Omigie, D., Pearce, M. T., & Stewart, L. (2012). Tracking of pitch probabilities in congenital amusia. *Neuropsychologia*, *50*(7), 1483–1493.

Parbery-Clark, A., Skoe, E., Lam, C., & Kraus, N. (2009). Musician enhancement for speech-in-noise. *Ear and Hearing*, *30*(6), 653–661. https://doi.org/10.1097/AUD.0b013e3181b412e9

Perani, D., Saccuman, M. C., Scifo, P., Spada, D., Andreolli, G., Rovelli, R., Baldoli, C., & Koelsch, S. (2010). Functional specializations for music processing in the human newborn brain. *Proceedings of the National Academy of Sciences*, *107*(10), 4758–4763. https://doi.org/10.1073/pnas.0909074107

Peretz, I. (2013). The biological foundations of music. In D. Deutsch (Ed.), *The psychology of music* (pp. 551–564). Elsevier.

Peretz, I. (2016). Neurobiology of congenital amusia. *Trends in Cognitive Sciences*, *20*(11), 857–867. https://doi.org/10.1016/j.tics.2016.09.002

Peretz, I., & Vuvan, D. T. (2017). Prevalence of congenital amusia. *European Journal of Human Genetics*, *25*(5), 625–630.

Peretz, I., Brattico, E., Jrvenp, M., & Tervaniemi, M. (2009). The amusic brain: In tune, out of key, and unaware. *Brain*, *132*(5), 1277–1286. https://doi.org/10.1093/brain/awp055

Peretz, I., Champod, A. S., & Hyde, K. (2003). Varieties of musical disorders: The Montreal battery of evaluation of Amusia. *Annals of the New York Academy of Sciences*, *999*, 58–75. https://doi.org/10.1196/annals.1284.006

Peretz, I., Cummings, S., & Dubé, M. P. (2007). The genetics of congenital amusia (tone deafness): A family-aggregation study. *The American Journal of Human Genetics*, *81*(3), 582–588. https://doi.org/10.1086/521337

Lagrois, M. É., Peretz, I., & Zendel, B. R. (2018). Neurophysiological and behavioral differences between older and younger adults when processing violations of tonal structure in music. *Frontiers in Neuroscience*, *12*, 54. https://doi.org/10.3389/fnins.2018.00054

Royal, I., Vuvan, D. T., Zendel, B. R., Robitaille, N., Schönwiesner, M., & Peretz, I. (2016). Activation in the right inferior parietal lobule reflects the representation of musical structure beyond simple pitch discrimination. *PLoS ONE*, *11*(5), e0155291. https://doi.org/10.1371/journal.pone.0155291

Schellenberg, E. G. (2004). Music lessons enhance IQ. *Psychological Science*, *15*(8), 511–514. https://doi.org/10.1111/j.0956-7976.2004.00711.x

Schellenberg, E. G. (2006). Long-term positive associations between music lessons and IQ. *Journal of Educational Psychology*, *98*(2), 457–468. https://doi.org/10.1037/0022-0663.98.2.457

Spiegel, M. F., & Watson, C. S. (1984). Performance on frequency-discrimination tasks by musicians and nonmusicians. *The Journal of the Acoustical Society of America*, *76*(6), 1690–1695. https://doi.org/10.1121/1.391605

Thompson, N. C., Cranford, J. L., & Hoyer, E. (1999). Brief-tone frequency discrimination by children. *Journal of Speech, Language, and Hearing Research*, *42*(5), 1061–1068. https://doi.org/10.1044/jslhr.4205.1061

Tillmann, B., Gosselin, N., Bigand, E., & Peretz, I. (2012). Priming paradigm reveals harmonic structure processing in congenital amusia. *Cortex*, *48*(8), 1073–1078.

Trainor, L. J., & Hannon, E. E. (2013). Musical development. In D. Deutsch (Ed.), *The psychology of music* (pp. 423–497). Elsevier Academic Press.

Trainor, L. J., & Trehub, S. E. (1994). Key membership and implied harmony in Western tonal music: Developmental perspectives. *Perception & Psychophysics*, *56*(2), 125–132. https://doi.org/10.3758/BF03213891

Vuvan, D. T., Nunes-Silva, M., & Peretz, I. (2015). Meta-analytic evidence for the non-modularity of pitch processing in congenital amusia. *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior*, *69*, 186–200. https://doi.org/10.1016/j.cortex.2015.05.002

Vuvan, D. T., Zendel, B. R., & Peretz, I. (2018). Random feedback makes listeners tone-deaf. *Scientific Reports*, *8*(1), 1–11. https://doi.org/10.1038/s41598-018-25518-1

Wechsler, D. (2003). *Wechsler intelligence scale for children (WISC-IV)* (4th ed.). The Psychological Corporation.

Zendel, B. R., & Alexander, E. J. (2020). Autodidacticism and music: Do self-taught musicians exhibit the same auditory processing advantages as formally trained musicians? *Frontiers in Neuroscience*, *14*, 752. https://doi.org/10.3389/fnins.2020.00752

Zendel, B. R., Lagrois, M. E., Robitaille, N., & Peretz, I. (2015). Attending to pitch information inhibits processing of pitch information: The curious case of amusia. *Journal of Neuroscience*, *35*(9), 3815–3824. https://doi.org/10.1523/JNEUROSCI.3766-14.2015

How to cite this article: Zendel, B. R., Demirkaplan, Ö., Mignault-Goulet, G., & Peretz, I. (2022). The relationship between acoustic and musical pitch processing in adolescents. *International Journal of Developmental Neuroscience*, *82*(4), 314–330. https://doi.org/10.1002/jdn.10181