Enhancement of auditory cortical development by musical experience in children

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Auditory evoked potentials (AEPs) express the development of mature synaptic connections in the upper neocortical laminae known to occur between 4 and 15 years of age. AEPs evoked by piano, violin, and pure tones were measured twice in a group of 4- to 5-year-old children enrolled in Suzuki music lessons and in non-musician controls. P1 was larger in the Suzuki pupils for all tones whereas P2 was enhanced specifically for the instrument of practice (piano or violin). AEPs observed for the instrument of practice were comparable to those of non-musician children about 3 years older in chronological age. The findings set into relief a general process by which the neocortical synaptic matrix is shaped by an accumulation of specific auditory experiences. *NeuroReport* 15:1917–1921 © 2004 Lippincott Williams & Wilkins.

Key words: Auditory cortex; Auditory evoked potentials; Electroencephalography; Musical training; Nature/nurture; Neuroplasticity

INTRODUCTION

Development of the human auditory cortex follows a distinctive time course revealed by anatomical data [1]. Neurons are in place in all layers of the auditory cortex at birth, but the matrix of synaptic connections among the neurons is rudimentary. Mature connections form in the lower infragranular layers of auditory cortex after 5 months of age and reach adult levels by 5 years. However, mature connections do not begin to develop in superficial layers II and upper III until 5 years of age, and reach adult levels around 12 years [1]. This developmental process is strongly expressed by auditory evoked potentials (AEPs) of the electroencephalogram [2,3], which reflect synchronized neural activity dependent on mature synapses in the cortex [4–6]. We investigated whether AEP correlates of these developmental processes are influenced by specific auditory experience.

Previous studies indicated that the P1 component of the AEP (frontal-positive scalp potential with amplitude maximum at about 90 ms in children) is prominent before 5 years of age, increases slightly in amplitude until about 10 years of age, and decreases thereafter [6,7]. The vertex-negative N1b (latency about 100 ms, called N1 herein) emerges around 5 or 6 years of age [6,8], increases substantially in amplitude until 10–12 years of age, and then decreases somewhat while remaining prominent into adulthood [6–8]. The P2 (vertex-positive, latency about 200 ms) follows a similar developmental course as the N1, reaching an amplitude maximum at 10–12 years of age, and persisting into adulthood [6,7]. In adult monkeys, N1 is generated by current sinks (depolarizations) in the superficial neocortical layers [9]; N1 thus appears to reflect the matrix of mature synaptic connections that is forming in these laminae after the age of 5 years in humans. P2 appears to reflect current sinks occurring in the deeper neocortical layers, most likely consequent on or overlapping with N1 processing, creating current sources more superficially [9]. In adult humans, cortical sources of the N1 and P2 are centered mainly within secondary auditory cortex (A2) [10,11] (belt and parabelt regions, Hackett *et al.* [12]). Recent neuromagnetic coregistrations using high resolution morphometry have identified two P1 sources arising from primary auditory cortex (A1) [13]. Interestingly, the layer-specific stages of cortical maturation assessed in anatomical data apply simultaneously to A1 and A2 [1].

In recent years, musicians have been used as a model for experience-induced plasticity [14], which is known to be expressed in AEPs in adults [11,15]. Here, for the first time, we compare AEPs evoked by pure, violin, and piano tones in young 4- to 5-year-old children enrolled in Suzuki music lessons with those of age-matched non-musician children. Our goal was to assess whether AEP components are sensitive to musical experience at this age and, if so, which components are affected. In addition, before conducting the main study we measured AEP responses in independent cohorts of non-musician children between 4 and 15 years of age to the same tones. These cross-sectional data provided a baseline against which to compare AEPs measured in children receiving musical training with older non-musician cohorts.

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MATERIALS AND METHODS

Subjects: The cross-sectional sample contained 24 normally developing children with no formal musical training, aged 4–5 (n=5), 6–7 (n=6), 8–9 (n=5), 10–12 (n=4), and 13–15 (n=4) years. The training sample contained six pianists and one violinist from the Hamilton Suzuki School of Music (4.5 ± 0.5 and 5.6 ± 0.4 years at the first and second measurements, respectively; three male, four female) and six age-matched control children with no musical training (4.76 ± 0.4 and 5.58 ± 0.5 years; 3 male, 3 female). Questionnaires revealed that the Suzuki students experienced much more music in their homes than did controls. Six of the seven Suzuki students, but only one control child, had at least one parent who practiced a musical instrument at home.

Stimuli: The stimuli were identical to those of Shahin *et al.* [16], consisting of 500 ms pure, violin, and piano tones (fundamentals A3 or 220 Hz, C3 or 131 Hz). They were matched in loudness and presented at ~70 dB over a flat response custom loudspeaker using an AW 32 sound card and Hafler P1000 amplifier.

Procedure: This research was approved by the McMaster University Ethics Research Board. Consent was obtained from both the children and their parents.

Children in the cross-sectional sample were tested once. The Suzuki students (and age-matched controls) were tested twice, just prior to music lesson commencement and again 1 year later. Parents completed a questionnaire about their family's musical environment.

AEPs were recorded from an EEG cap (Neuromedical QuickCap) using a Neuroscan Synamps amplifier (DC to 100 Hz sampled at 1 kHz) and referenced to Cz with a ground at AFz. All impedances were <10 kOhms. A total of 720 tones were presented in random order with a fixed ISI of 2.5 s offset-to-onset in a single experimental session (45 min) while children watched a silent movie.

Data analysis: EEG files were band-passed filtered between 1.5 and 20 Hz and epoched into 600 ms segments (including 100 ms baselines). Trials containing shifts of $\pm 200\,\mu V$ or greater in any channel were rejected. Channels containing unacceptable artifact in single subjects were taken out of the analysis across all subjects. Accepted trials (mean 86%, range 75–99%) were averaged according to tone type collapsing over C3 and A3 tones to enhance the signal-to-noise ratio, and re-referenced to a common average reference. The final electrode configuration included frontal channels Fz, F_3, F_4, F_7, F_8, central channels Cz, C_3, C_4, T_7, T_8, and parietal channels Pz, P_3, P_4, P_7, P_8.

AEP component peak latencies were determined from root mean square (RMS) amplitudes. For N1, the waveforms were rebaselined to the P1 peak. Grand average waveform peaks were used to define latency windows for peak measurement in individuals: P1: 50–130, N1: 90–160, P2: 130–200 ms.

No significant effects were found between the first and second measurements, so subsequent analyses were collapsed across this variable. ANOVAs were conducted on P1, P2, and N1 amplitude measured at their amplitude maxima (electrodes (F3 + F4)/2 for P1, Cz for N1 and P2) with group (Suzuki, non-musician), stimulus (pure, violin, piano tone), and AEP (P1, P2, N1) as factors where appropriate. Preplanned *post hoc* comparisons were made by the least significant difference (LSD) test. These analyses were repeated for P1, P2, and N1 latency, but no significant effects were found for this variable.

Source analysis was performed for P1, N1, and P2 responses, using average-referenced waveforms collapsed across the two groups. N1 waveforms were rebaselined to the P1 peak prior to fitting. For each AEP, two regional sources were seeded (one in each hemisphere) using BESA 2000 and iteratively fitted to the region that maximized the goodness of fit. Once locations were determined, the regional dipoles were transformed into single equivalent dipoles with orientations reflecting the uniqueness of each component. Goodness of fit exceeded 90% for each AEP.

RESULTS

Figure 1 shows AEPs for the cross sectional data. P1 (light traces) was clearly present at all ages and showed maximal amplitude at about 8–9 years of age. N1 and P2 responses (dark traces) increased until 10–12 years of age and diminished somewhat thereafter [6–8]. N1 and P2 were largest for piano tones, which were spectrally rich and had abrupt onsets. The development of AEPs during the time when synaptic maturation is occurring in superficial neocortical layers [1] suggests that synchronized activity in these layers is crucial for their appearance.

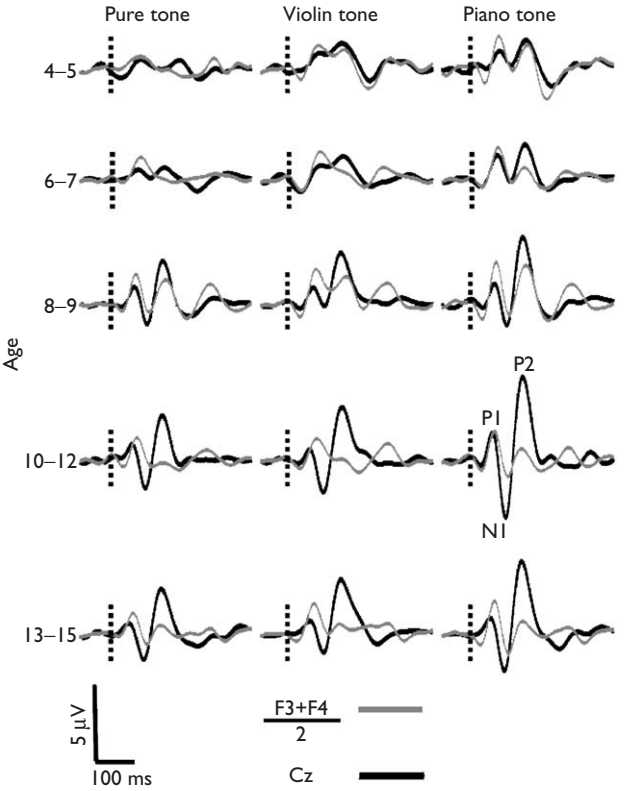

Fig. 1. Development of auditory evoked potentials elicited by violin, piano, and pure tones. Tone onset is indicated by a dotted vertical line. P1 reaches a maximum at frontal sites (F3, F4) at 8–9 years, and N1 and P2 at the vertex (Cz) at 10–12 years.

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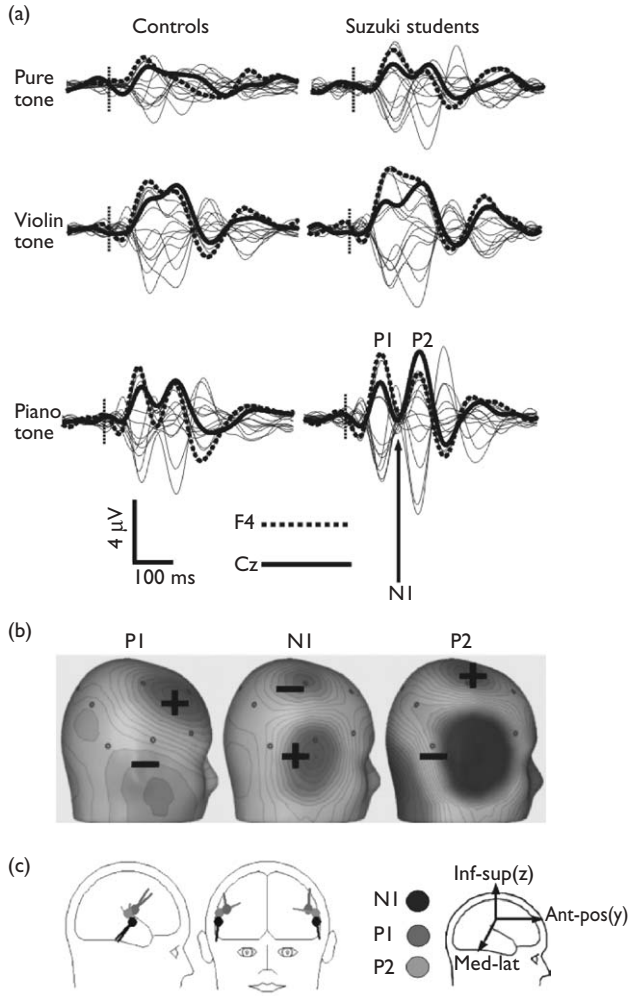

Fig. 2. AEP responses in 4- to 5-year-old Suzuki and non-musician controls. (**a**) Tone onset is indicated by a dotted vertical line. The two clear dipolar patterns apparent across the 15 channels correspond to P1 and P2. An intervening N1 is seen between P1 and P2 for piano tones, particularly in the Suzuki group. (**b**) Current source density maps for the piano tones collapsed across groups. P1 reached its amplitude maximum at frontal sites, N1 and P2 at the vertex. (**c**) Source-space solutions for piano tones (95% of the variance explained for P1 and P2, 91% for N1). The P2 source is radial and lateral with respect to the P1 source and the N1 source tangential, lateral and inferior with respect to the P1 source.

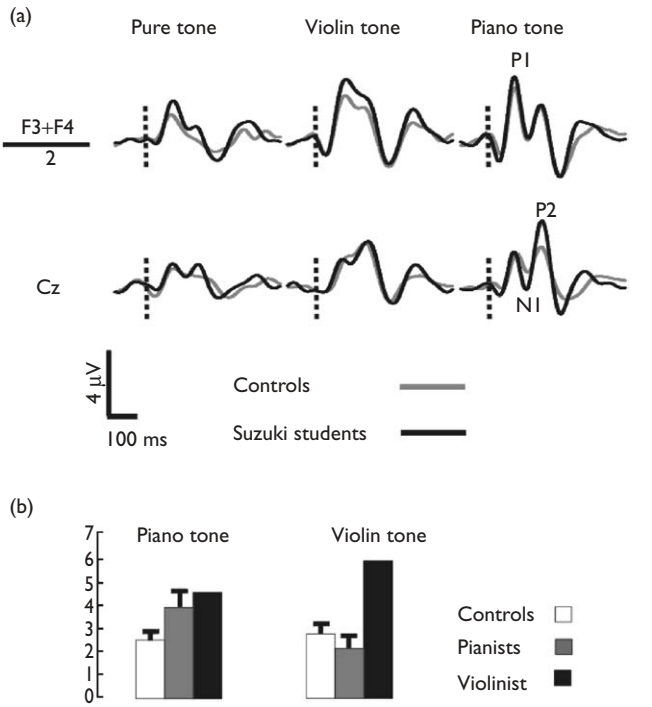

Fig. 3. AEPs in Suzuki and non-musician children. (**a**) N1 and P2 amplitude are enhanced in the Suzuki group only for piano tones (6 of the 7 Suzuki students played piano). The dotted vertical line denotes tone onset. (**b**) Timbre specificity. P2 amplitude evoked by the piano tones is larger in the Suzuki pianists (n=6) than in the non-musicians (n=6), but P2 evoked by the violin tones is not. P2 amplitude evoked by the violin tone is largest in the violinist (n=1) compared to the other groups and to P2 evoked by piano tones.

Suzuki and non-musician groups showed two clear dipolar patterns consistent with neuronal activations in auditory cortex, (Fig. 2a) corresponding to P1 (78 ms) and P2 (178 ms). P1 and P2 were generated in somewhat different regions of the auditory cortex (AEP × electrode interaction $F(14,168)=12.07$, $p<0.0001$). P1 was largest frontally, and P2 at the vertex (Fig. 2b). A small intervening N1 can also be seen in Fig. 2a, particularly for piano tones. Source analysis conducted for the piano tones, where AEPs were most developed, identified centers of activation in auditory cortex (Fig. 2c), with the shorter latency P1 falling medial to the later-occurring N1 and P2. This suggests a contribution from primary auditory cortex for P1 [13], and secondary auditory cortical sources for N1 and P2 [10,11].

Of most interest with respect to the question of the effects of musical training on early auditory cortical development were the differences between the Suzuki and non-musician groups. P1 amplitude was larger in the Suzuki than non-musician group across all stimuli ($F(1,11)=4.80$, $p=0.05$), suggesting that more neurons were depolarizing synchronously in primary auditory cortex in the Suzuki group (Fig. 3a). For both groups, P1 amplitude was larger for violin and piano tones than for pure tones, indicating that P1 was larger for the more spectrally rich sounds ($F(2,22)=9.39$, $p=0.001$; LSD *post hoc* contrasts were significant only between violin *vs* pure tones and piano *vs* pure tones, all $p<0.004$).

N1 responses could be reliably measured only for piano tones (Fig. 3a). Using root mean square waveforms, N1 amplitude was significantly larger in musician than non-musician children (main effect of group, $F(1,11)=17.17$, $p=0.002$). Six of the seven Suzuki pupils studied piano, suggesting that N1 enhancement was specific to the timbre of the instrument of training. However, we could not contrast musical and non-musical children for N1 differences evoked by violin and pure tones.

Across all children (Fig. 3a), P2 amplitude was largest for piano tones, intermediate for violin tones, and smallest for pure tones (main effect of tone, $F(2,22)=27.63$, $p=0.0001$; LSD *post hocs* all $p<0.005$). P2 amplitude also reflected differences in the children's experiences with the different musical instrument timbres. An interaction of tone with group ($F(2,20)=8.73$, $p=0.002$) reflected a larger P2 amplitude in the pianists than the non-musician for piano tones

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(LSD between groups $p<0.0008$) but not for violin or pure tones. To test this timbre specificity further, the P2 responses of the single violinist were compared to those of the six piano students (Fig. 3b). The P2 amplitude of the violinist in response to the violin tone, 5.94 μV, was 2.83 s.d. above the mean amplitude of the pianists, 2.14 ± 1.34 μV, and was larger than that of any other subject in the experiment. The probability of obtaining such a deviant score under the null hypothesis is 0.0027 assuming a normal distribution. On the other hand, the P2 amplitude of the violinist to the piano tone was 4.65 μV, which was within 1 s.d. of the mean for the pianists, (4.0 ± 1.9 μV). Comparison of Fig. 3a with Fig. 1 shows that P2 (and N1) amplitude evoked by piano tones in the Suzuki musicians resembled that of untrained children about 3 years older in chronological age.

DISCUSSION

Larger amplitude P1, N1, and P2 responses were found in 4- to 5-year-old musically experienced children compared with musically less experienced children. Furthermore, the P2 enhancement was specific to the instrument of practice. Thus AEPs differ between musical and control children as young as 4 years of age, and the differences reflect specific musical experience. Comparison of piano-evoked N1 and P2 responses in our 4- to 5-year-old musicians (most of whom were pianists) to cross sectional findings suggest that musical experience may have advanced the developmental trajectory for sounds of the instrument of training.

The fact that AEPs differed between groups prior to the Suzuki students' first formal music lessons raises questions with respect to possible innate contributions. While such factors could play a role, it is noteworthy that the early musical home environments provided by the parents also differed between the groups. The Suzuki children generally had at least one practicing musician in their home, and Suzuki parents typically prepare their children for music lessons through prior exposure to the musical instrument of instruction and the sounds that it makes. This early musical experience may account for the timbre-specific P2 and N1 enhancements that were seen for the instrument of practice. An innate argument would need to hypothesize that genes code for the perception of specific musical timbres, and that this coding is sufficient to determine choice of musical instrument regardless of other factors [17]. N1 and P2 are enhanced by laboratory training at acoustic discrimination in adult non-musicians, which confirms their sensitivity to remodeling by experience [11,15,18], and are larger in adult professional musicians compared to non-musicians when evoked by musical tones [16,19]. Stimulus-specific learning is likely affected by attention to the relevant stimuli as it is gated by the basal forebrain [20], although attention during our experiment was controlled by having the children watch an engaging silent video. Enhancement of the P1 in our Suzuki pupils, while stimulus non-specific, is consistent with previous reports of enhancements in adult musicians in primary auditory areas, as indexed by larger middle latency responses evoked by musical tones, and a larger volume of gray matter in Heschl's gyrus [21].

Results from animal studies support the hypothesis that functional neocortical development is enabled and guided by acoustic experience delivered to the maturing brain, with abnormal spectral experience degrading or enhancing areas of the cortical tonotopic map [22,23]. The interpretation that our P1, N1, and P2 enhancements in young music students are due in large part to their musical experience is also consistent with studies of children with early hearing loss who receive cochlear implants. Once the implant partially restores hearing, P1 development, reflecting inputs to middle layers of primary auditory cortex, proceeds at a similar rate to that of normal children, delayed by the period of auditory deprivation [2,24]. In contrast, the N1 and P2 components, reflecting the operation of mature synapses in superficial layers in secondary auditory areas, do not develop normally after an extended period of deprivation even when hearing is restored [2,24], suggesting that specific experience at specific stages of development is crucial for optimal development in these areas.

CONCLUSION

Our finding of AEP sensitivity to specific musical experience early in life is consistent with the hypothesis that the auditory scaffold is sculpted by experience in the developing brain [23,24]. This process appears to be expressed more robustly and in a more stimulus-specific manner in secondary than in primary auditory cortex. Presumably other auditory experiences such as learning a second language would also be expected to have general effects on the expression of P1 and language-specific effects on the expression of N1 and P2. Accordingly, the developmental trajectories of Fig. 1 reflect synaptic modifications induced by an accumulation of experience with complex sounds, and the differences between Suzuki music students and non-musician children shown in Fig. 2 and Fig. 3 reflect the effects of specific experience on the unique cortical networks that are set up in each individual person.

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