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The musical brain: brain waves reveal the neurophysiological basis of musicality in human subjects

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Abstract

To reveal neurophysiological prerequisites of musicality, auditory event-related potentials (ERPs) were recorded from musical and non-musical subjects, musicality being here defined as the ability to temporally structure auditory information. Instructed to read a book and to ignore sounds, subjects were presented with a repetitive sound pattern with occasional changes in its temporal structure. The mismatch negativity (MMN) component of ERPs, indexing the cortical preattentive detection of change in these stimulus patterns, was larger in amplitude in musical than non-musical subjects. This amplitude enhancement, indicating more accurate sensory memory function in musical subjects, suggests that even the cognitive component of musicality, traditionally regarded as depending on attention-related brain processes, in fact, is based on neural mechanisms present already at the preattentive level. © 1997 Elsevier Science Ireland Ltd.

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The neural basis of music perception, musical expertise, and musicality are far less understood than those of language and other higher forms of human cognition. Although for music perception, the significance of the right temporal lobe is widely accepted, e.g. [7,8], even this fundamental lateralization may apparently be altered, depending on the experimental paradigms used or the degree of the subjects' musical training [5,8,16].

The neuropsychological studies in music perception have focused in differentiating brain functions between musicians and non-musicians [3,4,6] to reveal the neural determinants of musical expertise. Meanwhile, the behavioral approach has addressed the divergent aspects of musicality, preceding musical expertise. First, musicality has been regarded as a sensory-level ability, for example, as an ability to discriminate tones of slightly different pitch or timbre [14,21]. Second, some authors have stressed the person's ability in noticing the holistic properties of music, like its meaning or aesthetic qualities [24]. Third, most recent views emphasized cognitive factors [12], like the person's ability to structure the ongoing flow of musical stimulation.

The present study addressed the neurophysiological basis of cognitive aspect of musicality by recording the mismatch negativity (MMN) component of the auditory event-related potential (ERP), e.g. [1,2,10,17,20,23]. The MMN is generated by preattentive [2] auditory-cortex [1,9,11] change-detection response elicited by any discriminable change in a repetitive sound, even when stimuli are attended [17]. It reflects a discrepancy between the incoming auditory information and the neural representation of the repetitive sound [10,17]. Since the MMN amplitude and latency strongly correlate with the behavioral discrimination of the stimulus change [13,14,18,23] it enables us to determine the accuracy of the central auditory system in encoding the auditory information.

The subjects (Musical, Nonmusical; $n = 15$ in both groups) were selected for ERP recordings on the basis of their performance in a cognitively-oriented musicality test from a total sample of 117 high-school or university students (for examples of test items, see Fig. 1A) [12]. The subject groups were roughly equal with respect to the formal

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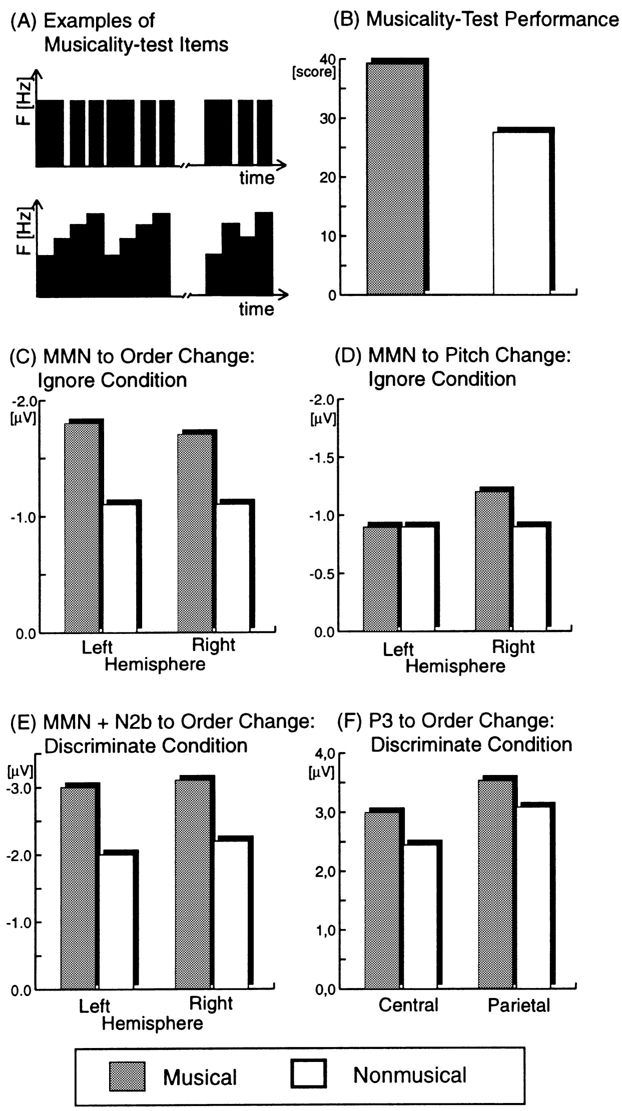

Fig. 1. (A) Example items of the musicality test employed in selecting subjects to Musical and Nonmusical groups. Each of the 40 test items began with a longer sequence in which a short pattern is repeated 3 or 4 times (for the sake of brevity the examples were shortened to 2 such pattern repetitions). After a short break, a comparison pattern was presented. The subject's task was to judge whether the comparison pattern equaled the repeated pattern of the preceding sequence. The patterns were formed either by varying the duration (top row), intensity, or pitch (bottom row) of the tones. In the illustrated examples, the comparison pattern equals the repeated pattern on the top row. (B) Mean performance of musical (gray) and non-musical (white) subjects in the musicality test. (C) The mean mismatch negativity (MMN) amplitude for musical and non-musical subjects in the Ignore Order-Change condition. On the left side, the bars illustrate the MMN amplitude recorded over the left hemisphere (Ll electrode) and on the right side, the MMN amplitude recorded over the right hemisphere (Rl electrode). (D) The mean MMN amplitude for musical and non-musical subjects in the Ignore Pitch-Change condition. (E) The mean MMN + N2b amplitude for musical and non-musical subjects in the Discriminate Order-Change condition. (F) The mean P3 amplitude for musical and non-musical subjects in the Discriminate Order-Change condition. On the left side, the bars illustrate the P3 amplitude recorded at the vertex (Cz electrode) and on the right side, the P3 amplitude recorded at the parietal area (Pz electrode).

training received in music. All subjects were right-handed and had normal hearing. From each group, 1 subject was rejected because of too many extra-cerebral artifacts in the EEG. The remaining 14 subjects forming Musical group (19–24 years, average 21.4 years; 4 males) performed in the musicality test at the level of professional musicians (range 38–40/40, average score 39.3), although only 3 of them still took music lessons and 4 had never had any musical training outside school. The average score of the 14 subjects in Nonmusical group (18–33 years, average 25.5 years; 5 males) was 27.6 points (range 21–30/40). Seven of them had never received any musical training outside the school, while one was still participating in music lessons.

Auditory stimulation in the Order-Change Condition consisted of a continuously looped stream of four 125 ms tones (...E–F–G–A–E–F–G–A... of the middle octave of the Western musical scale, equaling...330–349–392–440... Hz). These stimuli were adapted from the musicality-test item illustrated in Fig. 1A, bottom row. To determine how accurately the temporal order of this tone pattern was automatically encoded by the auditory system, infrequent ($P = 0.1$) changes were embedded in the stream by occasionally reversing the order of two consecutive tones (E–G–F–A; 330–392–349–440 Hz). In the Pitch-Change Condition, frequent tone sequences forming C major chords (...C–E–G–C...; 262–330–392–523 Hz) were randomly ($P = 0.1$) replaced with sequences forming a C minor chord (...C–Eflat–G–C...; 262–311–392–523 Hz). There, a new pitch was introduced enabling us to determine the MMN to a relatively primitive stimulus change without the importance of temporal information. During these two conditions, subjects were instructed to read a self-selected book. In both conditions, there were 3 stimulus blocks, these 6 blocks being presented intermixed, their order being randomized between subjects. During the Discriminate Order-Change Condition, subjects' task was to indicate by a button press each time they detected any change in the stimulus. These 3 blocks were always presented last in order to avoid carry-over effects of attention to ignore conditions [18].

Stimuli, generated by a PC-based NeuroStim stimulation unit, were delivered binaurally via headphones at an intensity of 75 dB SPL, in series of 500 sound patterns (about 5 min each) without silent gaps between the successive patterns. Each tone was composed of 3 equiloud frequency components (e.g. 330 + 660 + 990 Hz) to avoid unnatural sinusoidal-tone stimulation (e.g. absolute-pitch possessors' pitch-naming [15] performance benefits if sounds include their overtones).

The EEG (0.1–100 Hz bandpass; 500 Hz sampling rate) was recorded with 10 electrodes, 4 at the midline (frontopolar (Fpz), frontal (Fz), central (Cz), parietal (Pz)) and 6 equidistantly along the tilted coronal line connecting the left (LM) and right (RM) mastoids through Fz (LM, L2, L1, (Fz), R1, R2, RM). Eye movements were monitored with Fpz and HEOG electrodes (horizontal EOG; attached to the

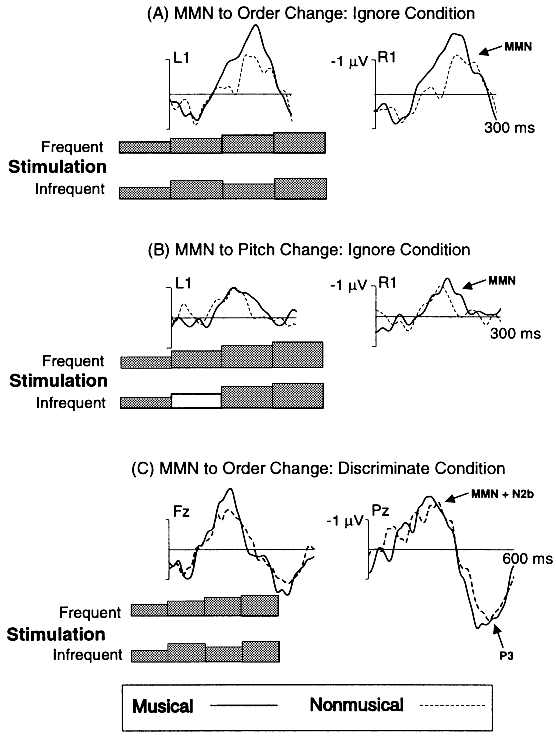

Fig. 2. (A) The MMN of musical (continuous line) and non-musical (dashed line) subjects in the Ignore Order-Change condition. The curves are difference waves in which ERPs for frequent tone patterns were subtracted from those for infrequent patterns. These responses were recorded at Ll and R1 electrodes. The timing of the stimulation is indicated below the curves and the MMN by the arrow. (B) The MMN of musical (continuous line) and non-musical (dashed line) subjects in the Ignore Pitch-Change condition. (C) The MMN + N2b and P3 waves of musical (continuous line) and non-musical (dashed line) subjects in the Discriminate Order-Change condition. These responses were recorded at midline electrodes Fz and P7.

right outer canthus). Epochs with EEG change exceeding 150 μV at any electrode were automatically omitted from averaging. The reference electrode was attached to the nose. ERPs were off-line averaged by using 700 ms analysis periods for the ignore Order-Change and Pitch-Change conditions and a 1100 ms analysis period for the discriminate Order-Change condition (a baseline of –200–0 ms before the deviant-element onset was employed in all conditions) and filtered (bandpass 1–30 Hz) separately for each condition, stimulus type, and subject. Thereafter, grand-average ERPs and difference waves (frequent-stimulus ERP subtracted from infrequent-stimulus ERP) were calculated for each condition, stimulus type, and group.

The MMN amplitudes were measured from the individual difference waves as the mean amplitude during the 30 ms time window centered at the MMN peak latency, which was determined from the grand-average difference waves between 150 and 300 ms. In the measurements, the Fz electrode values were referred to the average of the LM and RM recordings, L1 and L2 to LM, and R1 and R2 to RM. The N2b + MMN amplitude recorded during the discrimination task was measured from the difference waves as the mean voltage over the 30 ms time window individually centered at the most negative peak between 150 and 300 ms. The P3 amplitude was measured from the difference waves as the mean voltage over the 50 ms time window individually centered at the most positive peak between 400 and 700 ms. In these measurements, the amplitude values were referred to the nose electrode recordings.

The results showed that infrequent tone patterns elicited MMN in both groups in Order-Change and Pitch-Change Conditions (Figs. 1,2; Table 1), the MMN amplitude being significant at the frontal electrodes ($t(13) = 2.4–7\ \ 6$, $P < 0.05$ at L1, Fz, and R1; the difference wave contrasted by *l*-tailed *t*-test against zero). This implies that the pitch content of the sounds, as well as their order in the continuous stimulus stream, were preattentively encoded by the central auditory system by subjects of both groups.

In the Order-Change Condition, MMN was significantly larger in amplitude in musical than in non-musical subjects (Figs. 1C,2A; $F(1,26) = 4.29$, $P < 0.05$; 2-way ANOVA with factors Group (Musical, Nonmusical) and Electrode (L2, L1, Fz, R1 and R2)). In contrast, the MMN amplitude in the Pitch-Change Condition did not differentiate the 2 groups (Figs. 1D,2B; $F(1,26) = 0.12$, $P < 0.74$; 2-way ANOVA with factors Group (Musical, Nonmusical) and Electrode (L2, L1, Fz, R1 and R2)). This suggests that the musical subjects have more accurate neural representations for temporal stimulus information than the non-musical subjects, even in ignore condition, whereas no such difference

Table 1

Mean MMN (Ignore Conditions) and MMN + N2b (Discriminate Condition) amplitudes for rarely presented changed tone patterns.

Condition and component	Musical group subjects		Nonmusical group subjects		Group difference
	L1	R1	L1	R1	
Order Change,	–1.8	–1.7	–1.1	–1.1	P < 0.05
Ignore: MMN	(1.0)	(0.8)	(1.0)	(1.3)	
Pitch Change,	–0.9	–1.2	–0.9	–0.9	n.s.
Ignore: MMN	(1.2)	(1.0)	(1.1)	(1.4)	
Order Change,	–3.0	–3.1	–2.0	–2.2	P < 0.05
Discrimination: MMN + N2b	(2.1)	(1.2)	(1.1)	(1.1)	

The brain responses were recorded at Ll and R1 electrodes (above left and right frontotemporal cortex, respectively) from musical and non-musical subjects. The values are in microvolts; standard deviations are given in parentheses.

in neural mechanisms could be observed when the change in stimulation included a new pitch (change thus being sensory rather than cognitive).

In the Discriminate Order-Change Condition, order changes elicited 2 separate brain responses: a negative wave which composed of overlapping N2b [19] and MMN [1,17] components, and the subsequent decision-related late positive wave P3 [22]. The negativity was considerably larger in amplitude in musical subjects (Figs. 1E,2C; Table 1; $F(1,26) = 4.60$, $P < 0.05$; 2-way ANOVA with factors Group (Musical, Nonmusical) and Electrode (L2, L1, Fz, R1 and R2)). In contrast, the subsequent late positive wave did not differentiate the 2 groups (Figs. 1F,2C; $F(1,26) = 0.65$, $P < 0.43$; 2-way ANOVA with factors Group (Musical, Nonmusical) and Electrode (Fz, Cz and Pz)). This pattern of data indicates a dissociation between preattentive and attentive processes during the discrimination task which was highly demanding due to fast stimulation rate and missing feedback: the enhancement of the early negativity in musical subject indexes that the order changes were more accurately encoded by their auditory cortex than by the non-musical subjects' auditory cortex, however, without sufficiently triggering the subsequent change-detection mechanisms.

In conclusion, the present data showed that even in ignore condition the musical subjects' central auditory system responds more vigorously to temporal-order reversals in repetitive sound patterns than that of the non-musical subjects. This suggests that auditory-cortex based sensory memory encoded the auditory information structure more accurately in the musical than in the non-musical subjects. Thus, the structuring ability probed by the present musicality test relies on cortical functions which can be probed by ERP recordings even during a reading task. Consequently, the cognitive component of musicality, traditionally considered to depend on attentional high-level cognitive processes, in fact depends on brain mechanisms which operate already at the preattentive level. Further, since the MMN to pitch changes did not significantly differ between these 2 groups, the brain prerequisites of the cognitive and sensory components of musicality are, at least to a great extent, separate.

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[1] Alho, K., Cerebral generators of mismatch negativity (MMN) and its magnetic counterpart (MMNm) elicited by sound changes, Ear Hearing, 16 (1995) 38–51.
[2] Alho, K., Woods, D.L. and Algazi, A., Processing of auditory stimuli during auditory and visual attention as revealed by event-related potentials, Psychophysiology, 31 (1994) 469–479.
[3] Besson, M. and Faïta, F., An event-related potential (ERP) study of musical expectancy: comparison between musicians and non-musicians, J. Exp. Psychol.: Hum. Percept. Perf., 21 (1996) 1278–1296.
[4] Besson, M., Faïta, F. and Requin, J., Brain waves associated with musical incongruities differ for musicians and non-musicians, Neurosci. Lett., 168 (1994) 101–105.
[5] Bever, T.G. and Chiarello, R.J., Cerebral dominance in musicians and non-musicians, Science, 185 (1974) 537–539.
[6] Crummer, G.C., Walton, J.P., Wayman, J.W., Hantz, E.C. and Frisina, R.D., Neural processing of musical timbre by musicians, non-musicians, and musicians possessing absolute pitch, J. Acoust. Soc. Am., 95 (1994) 2720–2727.
[7] Damasio, A.R. and Damasio, H., Musical faculty and cerebral dominance. In M. Critchley and R.A. Henson (Eds.), Music and the Brain, Camelot Press Ltd., Southampton, 1978, pp. 141–155.
[8] DePascalis, V., Marucci, F.S., Penna, M.P. and Labbrozzi, D., Event-related potentials in musically sophisticated and unsophisticated subjects: a study on hemispheric specialization, Neuropsychology, 25 (1987) 947–955.
[9] Giard, M.-H., Perrin, F., Pernier, J. and Bouchet, P., Brain generators implicated in the processing of auditory stimulus deviance: a topographic event-related potential study, Psychophysiology, 27 (1990) 627–640.
[10] Gomes, H., Ritter, W. and Vaughan, H.G. Jr., The nature of preattentive storage in the auditory system, J. Cogn. Neurosci., 7 (1995) 81–94.
[11] Hari, R., Hämäläinen, M., Ilmoniemi, R., Kaukoranta, E., Reinikainen, K., Salminen, J., Alho, K., Näätänen, R. and Sams, M., Responses of the primary auditory cortex to pitch changes in a sequence of tone pips: neuromagnetic recordings in man, Neurosci. Lett., 50 (1984) 127–132.
[12] Karma, K., Auditory and visual temporal structuring: how important is sound to musical thinking?, Psychol. Music, 22 (1994) 20–30.
[13] Kraus, N., McGee, T., Carrell, T.D. and Sharma, A., Neurophysiologic bases of speech discrimination, Ear Hearing, 16 (1995) 19–37.
[14] Lang, A.H., Nyrke, T., Ek, M., Aaltonen, O., Raimo, I. and Näätänen, R., Pitch discrimination performance and auditive event-related potentials. In C.H.M Brunia, A.W.K. Gaillard, A. Kok (Eds.), Psychophysiological Brain Research, Vol. I, Tilburg University Press, Tilburg, 1990, pp. 294–298.
[15] Lockhead, G.R. and Byrd, R., Practically perfect pitch, J. Acoust. Soc. Am., 70 (1981) 387–389.
[16] Mazziotta, J.C., Phelps, M.E., Carson, R.E. and Kuhl, D.E., Tomographic mapping of human cerebral metabolism: auditory stimulation, Neurology, 32 (1982) 921–937.
[17] Näätänen, R. Attention and Brain Function, Lawrence Erlbaum, Hillsdale, NJ, 1992.
[18] Näätänen, R., Schröger, E., Karakas, S., Tervaniemi, M. and Paavilainen, P., Development of neural representations for complex sound patterns in the human brain, NeuroReport, 4 (1993) 503–506.
[19] Novak, G., Ritter, W. and Vaughan, H.G. Jr., The chronometry of attention-modulated processing and automatic mismatch detection, Psychophysiology, 29 (1990) 412–430.
[20] Ritter, W., Deacon, D., Gomes, H., Javitt, D.C. and Vaughan, H.G., Jr, The mismatch negativity of event-related potentials as a probe of transient auditory memory: a review, Ear Hearing, 16 (1995) 52–67.
[21] Seashore, C., Psychology of Music, Dover Publications Inc., New York, 1938.
[22] Sutton, S., Braren, M., Zubin, J. and John, E.R., Evoked potential correlates of stimulus uncertainty, Science, 150 (1965) 1187–1188.
[23] Tiitinen, H., May, P., Reinikainen, K. and Näätänen, R., Attentive novelty detection in humans is governed by pre-attentive sensory memory, Nature, 372 (1994) 90–92.
[24] Wing, H., Manual for Standardised Tests of Musical Intelligence, City of Sheffield Training College, Sheffield, 1948.