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Hemispheric Asymmetries in the Perception of Rapid (Timbral) and Slow (Nontimbral) Amplitude Fluctuations of Complex Tones

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Hemispheric asymmetries for processing rapid (timbral) and slow (nontimbral) amplitude fluctuations of complex tones were investigated in 32 right-handed nonmusicians. Two monaural matching-to-sample tests with contralateral white noise and attention directed to 1 ear were used, 1 with tones presenting slow fluctuations of amplitude and 1 with tones presenting rapid fluctuations of amplitude perceived as different timbres. Stimuli were generated by altering the amplitude envelope of a steady state complex tone. Dependent variables were reaction time and accuracy. The results suggest an important role for the right hemisphere in the perception of temporal variations of intensity of sounds both when these variations are rapid and perceived as timbral qualities and when they are slow and perceived as changes of loudness.

Musical timbre, defined as “that attribute of auditory sensation in terms of which a listener can judge that two sounds similarly presented and having the same loudness and pitch are dissimilar” (definition of the American Standards Association, as cited in Moore, 1997, p. 246), is a multidimensional attribute of sound that depends both on stationary (spectral) and nonstationary (temporal) cues (Balzano, 1986; Berger, 1964; Clark, Robertson, & Luce, 1964; Saldanha & Corso, 1964; Wedin & Goude, 1972). Nonstationary cues include parameters such as the characteristics of the onset and decay and rapid fluctuations of the amplitude or of the spectral composition of the sound.

Various investigations on hemispheric asymmetries for timbre perception have shown that a right-hemisphere dominance can be demonstrated for musical sounds, that is, for sounds that are generated by different musical instruments and that normally vary both in spectral and in temporal characteristics (Boucher & Bryden, 1997; Kallman, 1978; Kallman & Corballis, 1975; Prior & Troup, 1988; Risset & Wessel, 1982). Although these studies did not allow researchers to determine the specific contributions of stationary and nonstationary cues to laterality, the finding of a right-hemisphere dominance for natural timbres was generally considered as an example of the well-known superiority of the right hemisphere for tasks requiring frequency analysis of the signals (Milner, 1962; Samson & Zatorre, 1994; San Martini, Filetti, Marangon, & Tasin, 1994; Sidtis & Volpe, 1988; Tramo & Gazzaniga, 1989; Zatorre, 1988).

More recently, two studies have demonstrated that there is also right-hemisphere dominance for the perception of the temporal cues of timbre, such as the onset, the decay, or the rapid fluctuations of the amplitude envelope of the sound. Samson and Zatorre (1994) investigated the effects of cerebral lesions on the ability to discriminate timbres differing in temporal components. They used two timbre discrimination tasks, one based on spectral cues (number of harmonics) and one on temporal cues (onset duration). They found that patients with right temporal damage did not perform as well as patients with left temporal damage and control participants in both tasks. In a dichotic study on neurologically intact participants, Brancucci and San Martini (1999) used timbre differences conveyed by rapid fluctuations of the amplitude of a complex tone and found a left-ear advantage, indicative of right-hemisphere dominance. These findings seem to contradict the generally accepted dichotomy according to which, whereas the harmonic integration of sounds is primarily a function of the right hemisphere, the temporal integration of auditory events mainly involves left-hemispheric structures (Carmon & Nachshon, 1981; Efron, 1963; Gordon, 1978; Kester et al., 1991; Swisher & Hirsch, 1972; Tallal & Newcombe, 1978).

A different interpretation is possible, however. Temporal and spectral cues of timbre interact at a physical level. Rapid changes of the amplitude envelope of an otherwise constant sound tend to introduce inharmonic components into its frequency spectrum that are generally confined to the lower frequency region. It may be argued that these inharmonic components, although of low amplitude, play a decisive role in the perception of timbre. Rapid changes of amplitude that are normally perceived holistically as timbral qualities may in fact be processed in the frequency rather than the time domain, thus leading to an advantage of the right hemisphere, as expected on the basis of the dichotomy mentioned above. According to this interpretation, one should expect that the advantage of the right hemisphere occurs only when the amplitude variations are sufficiently rapid to provide inharmonic spectral cues of timbral interest and that it reverses (or becomes smaller) when they are

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slow, unlikely to generate inharmonic components of any relevance, and perceived as changes of intensity over time.

As an approach to this issue, in this study we investigated, within a matching-to-sample task with contralateral white noise, the ear advantage produced by two classes of amplitude fluctuations: slow fluctuations that are perceived as changes of intensity over time and rapid fluctuations that are perceived holistically as timbral qualities.

Method

Participants

Thirty-two neurological intact participants (22 female and 10 male) ages 22 to 35 years (mean age = 26.6, *SD* = 4.1), volunteered to take part in the experiment. They all declared they were right-handed, and this was borne out by a hand preference questionnaire (Salmaso & Longoni, 1985). None complained of any auditory impairment, but no direct assessment of auditory function was performed. All participants were nonmusicians, that is, they were not practicing any musical instrument on a regular basis and they had not had any formal musical education.

Stimuli

The stimuli were synthesized on a Pentium 166 PC with Sound Blaster audio card (Model AWE 32; Microweve, Rome, Italy), using the CSound language (Vercoe, 1992) for sound synthesis. The following procedure was used in order to obtain six sounds with the same spectral composition and different amplitude envelopes. First, six complex tones with identical frequency spectrum, pitch, and intensity were generated, summing up the first eight harmonics of a fundamental of 500 Hz. Then, their amplitude envelopes were differentially modulated, keeping total and peak amplitude identical among the tones. In this way, two sets of three “slow” and three “rapid” tones each were obtained. Of the slow tones, one had a regularly increasing envelope, one had a regularly decreasing envelope, and the third had an envelope regularly increasing in the first half and regularly decreasing in the second half. Of the rapid tones, the first was characterized by a rise time of 65 ms, followed by sawtooth intensity fluctuations of 6.67 Hz, followed by a decay time of 200 ms. The second had a rise time of 70 ms, sawtooth intensity fluctuations of 40 Hz, and a decay time of 200 ms. The third had a rise time of 10 ms, followed by a steady state of 560 ms and a decay of 430 ms.

To confirm that the two sets of tones were predominantly perceived as varying, respectively, only in timbre or only in their intensity contours, we presented them, in preliminary trials, to five judges, who were nonmusicians and naive with respect to the aims of the study. All possible consecutive pairs of rapid or slow tones were formed and binaurally delivered in a random order. Each pair was presented six times. Judges were forced to respond as to whether they perceived the tones within each pair as “different timbres” or as “tones varying in intensity over time in different ways.” Judges agreed 100% of the time that rapid tones differed in timbre and slow tones differed in their intensity contours.

Power spectra and amplitude envelopes of the stimuli are shown in Figures 1, 2, and 3. Sampling rate was 44.1 kHz, and amplitude resolution was 16 bit. To ensure that no transients or undesired alterations were present in the stimuli, we recorded them from the headphones and reanalyzed them.

Design and Procedure

Participants were presented with two matching-to-sample tests with contralateral white noise, both involving monaural target presentation and attention directed to one ear (the ear that received the monaural target). This format was chosen because previous studies with musical materials have shown that it allows the detection of a consistent and reliable laterality effect (Brancucci & San Martini, 1999; San Martini, De Gennaro, Filetti, Lombardo, & Violani, 1994; San Martini, Filetti, et al., 1994; San Martini & Quarta, 1989). One test contained only slow stimuli, and the other test contained only rapid stimuli. Both tests were composed of 192 trials separated by 2-s intertrial intervals. Each trial consisted of the following sequence: one monaural target tone (1 s), followed by a pause (1 s), followed by a pair consisting of one monaural probe tone (1 s) and a contralateral burst of white noise beginning 50 ms before the tone and ending 50 ms after it, so that the probe tone was delivered when the noise was in its steady state (unlike the probe tones, the target tones were always presented without contralateral white noise). In the steady state phase, the

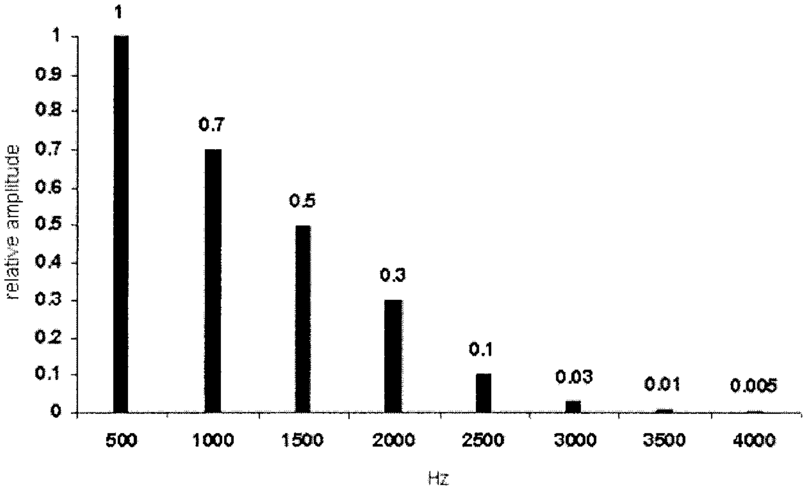

Figure 1. Basic frequency spectrum of all stimuli.

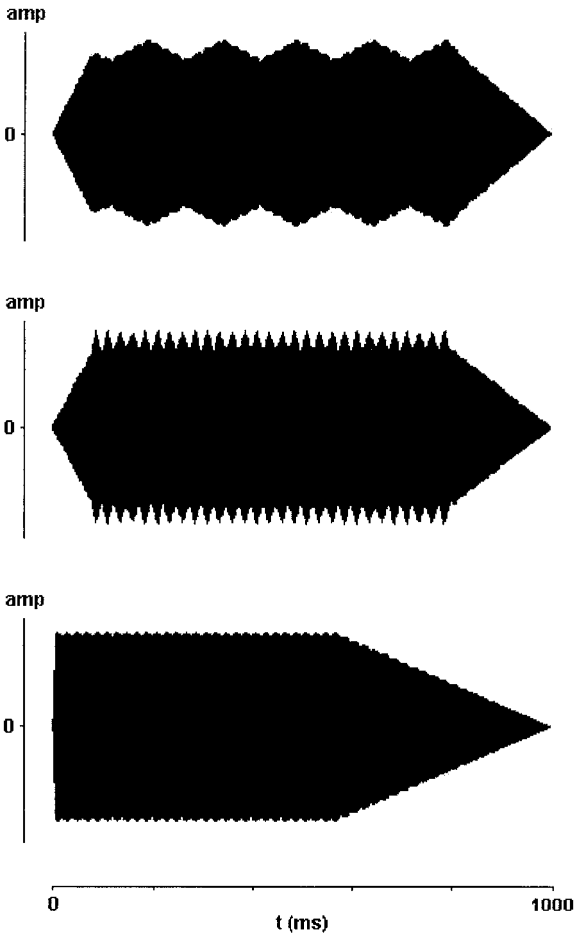

Figure 2. Amplitude (amp) envelopes of the rapidly fluctuating stimuli. Peak amplitude = 74 dB (A); *t* = time.

intensity of the white noise was 74 dB (A). Half of the probes matched the target. When there was no matching, both (mismatching) probes were equally likely.

In both tests, the 192 trials were grouped into 32 blocks of 6 trials each. Trials were allocated to blocks on a random basis, with the constraint that "matching" should occur more than once and less than five times. The side of presentation of the target stimulus changed with every block. The blocks were separated by a 4-s interval. Each block was preceded by a beep (200 ms), which was presented monaurally to the ear that was to receive the subsequent target stimuli of that block. Participants were instructed to direct their attention to the side of the monaural beep during the subsequent block and were informed that both targets and probes would be delivered to that side. Side of presentation of the target stimuli was blocked rather than randomized in order to facilitate allocation of attention to the requested side.

The two tests were administered separately in two sessions separated by 2 weeks, with the order of tests counterbalanced across participants. The experiment was completely automated by means of Visual Basic software. Participants wore a pair of headphones (Model AKG K100, with impedance of 100 W and sensitivity of 103 dB/mW; Ricordi, Rome, Italy) and were comfortably seated at a table in front of a computer monitor (approximately 70 cm from the participant's head) with both hands lying on the keyboard. Participants were instructed to look at a green circle in the center of the screen in front of them and not to shift their gaze laterally if possible during the experiment. Compliance with this instruction was not directly controlled. In a first familiarization phase, participants were invited to listen to the sounds that were to be used in the subsequent test until they felt familiar with them. In the experimental phase, participants were presented with the test twice (96 + 96 trials), the second time with the headphones rotated between the ears. The initial orientation of the headphones was counterbalanced across participants. The intensity level of the sounds was identical in both earphones, 74 dB (A) intensity at peak, as measured by a phonometer. Participants had to communicate whether the binaural pair (probe and contralateral white noise) they had just heard contained the target by pressing one of two keys on the keyboard as fast as possible. They were instructed to press a key for "yes" with their left forefinger and a key for "no" with their right forefinger. No feedback was provided. The association between hand and type of response ("yes," "no") was not counterbalanced. Type and latency of response were automatically stored for later analysis. Each experimental session lasted approximately 30 min.

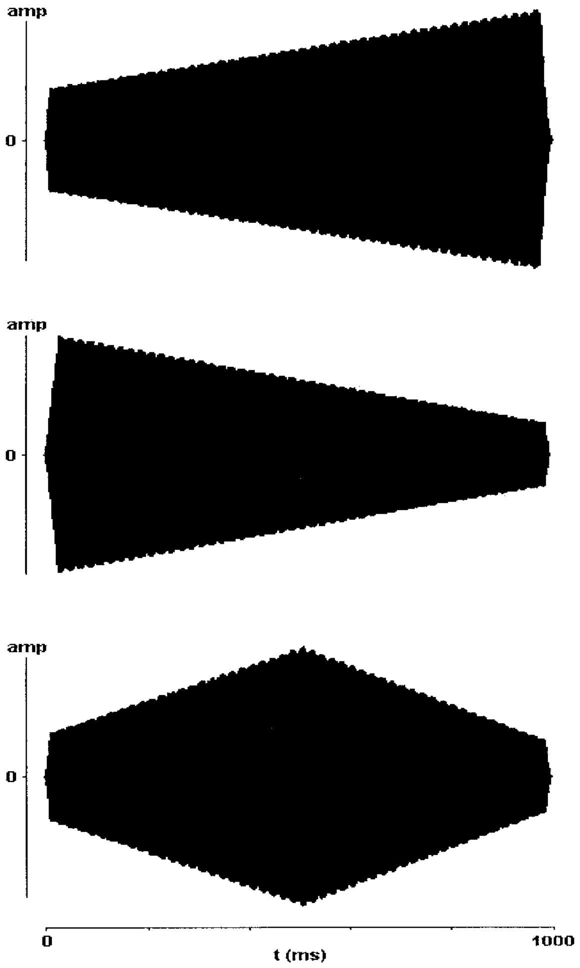

Figure 3. Amplitude (amp) envelopes of the slowly fluctuating stimuli. Peak amplitude = 74 dB (A); *t* = time.

Results

The dependent variables were reaction time and number of errors. Reaction time was measured as the median latency of correct responses.

All the statistical analyses were performed on the raw scores, as Kirk's (1968, pp. 66–67) method suggested that no transformation of the data (for either reaction time or number of errors) was required to meet the homoscedasticity assumption.

Preliminary Analyses

Preliminary analyses of variance indicated that earphone position, the order of test administration (whether participants first received the rapid or the slow test), and the sex of the participants did not influence the dependent variables, as they showed no main or interaction effects. These variables were therefore not included in subsequent analyses.

As "yes" and "no" key-press responses were not counterbalanced across the right and the left hand, a response bias of any kind could affect the reaction time results. To evaluate this potential confound, we performed an analysis to assess whether our participants tended to make left- and right-hand responses with similar frequencies. The mean number of correct and incorrect "yes" and "no" responses for both the rapid and the slow test is shown in Table 1. Overall, there were no significant differences between the mean number of "yes" and the mean number of "no" responses in the rapid test, $t(31) = 1.29$, $p = .21$, and in the slow test, $t(31) = 1.44$, $p = .16$. Subsequent analyses showed that errors were equally distributed between false alarms and misses: rapid test, $t(31) = 1.09$, $p = .29$; slow test, $t(31) = 0.22$, $p = .82$. A 2 × 2 analysis of variance (ANOVA) on the relative proportion of misses and false alarms, with type of test and ear of presentation as factors, showed no significant effects of the type of test, $F(1, 30) = 0.50$, $p = .48$; of the ear, $F(1, 30) = 3.60$, $p = .06$; and of the interaction, $F(1, 30) = 1.57$, $p = .21$.

Main Analyses

Mean values for both variables are depicted graphically as a function of ear of presentation and type of test in Figure 4. Means and standard errors are presented in Table 2.

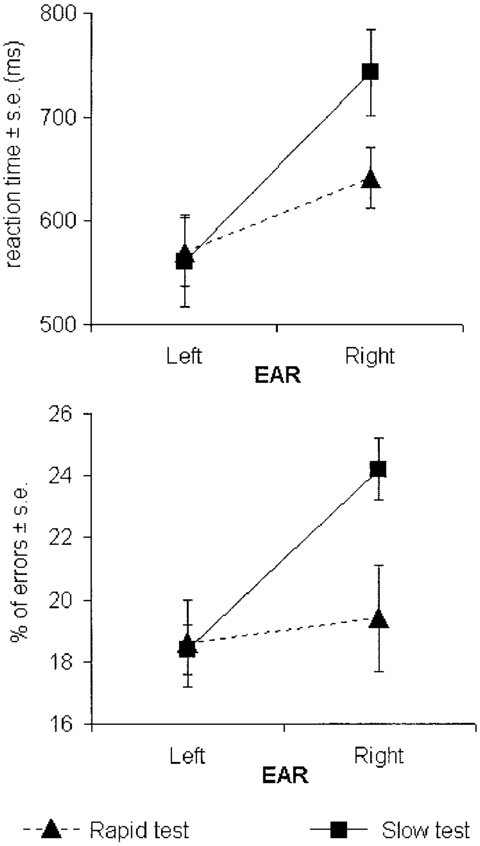

Figure 4. Mean values of (median) reaction time and percentage of errors as a function of ear of presentation for the rapid (timbral) and the slow (nontimbral) test.

A 2 × 2 repeated measures ANOVA with ear of input and type of test as independent variables was carried out for both dependent variables.

Regarding reaction time, there was no main effect for type of test, $F(1, 31) = 0.60$, $p = .44$; a significant main effect for ear, $F(1, 31) = 49.68$, $p < .01$, with a shorter reaction time for the left ear; and a significant Ear × Type of Test interaction, $F(1, 31) = 8.63$, $p = .016$. Subsequent analyses of the simple main effects showed that the left-ear advantage, in terms of shorter reaction times, was signifi-

Table 1
Mean Number of Correct and Incorrect Responses to Tests

	"Yes" response[a]				"No" response[b]			
	Hits		False alarms		Correct rejections		Misses	
Test	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
Rapid (timbral)	75.7	4.7	19.1	1.7	79.9	3.4	17.3	1.3
Slow (nontimbral)	74.5	0.7	20.3	1.1	76.4	1.2	20.8	1.5

[a] For the rapid test, the mean number of "yes" responses was 94.8 ($SD = 5.5$); for the slow test, the mean number of "yes" responses was 94.8 ($SD = 0.8$). [b] For the rapid test, the mean number of "no" responses was 97.3 (SD = 5.5); for the slow test, the mean number of "no" responses was 97.2 ($SD = 0.8$).

Table 2
Mean Reaction Times and Percentages of Errors on Tests

	Reaction time (ms)				% error			
	Left ear		Right ear		Left ear		Right ear	
Test	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
Rapid (timbral)	570	33	641	29	18.6	1.4	19.4	1.7
Slow (nontimbral)	561	44	743	42	18.4	0.8	24.2	1.0

cant both for the rapid test ($p = .01$) and for the slow test ($p < .01$) and that the type of test effect was significant for the right ear ($p < .001$), with a better performance in the rapid test, but not for the left ear ($p = .72$). According to Cohen's (1977) classification system, the size of the ear effect was above "large" in the slow test ($d = 1.91$) and just above "medium" in the rapid test ($d = 0.57$).

Regarding the number of errors, there was no main effect for type of test, $F(1, 31) = 0.85$, $p = .36$; a significant main effect for ear, $F(1, 31) = 10.62$, $p = .03$; and a significant Type of Test × Ear interaction, $F(1, 31) = 6.94$, $p = .01$. Subsequent analyses of the simple main effects showed that there was a significant left-ear advantage (less errors) for the slow test ($p < .01$) but not for the rapid test ($p = .51$) and that there was a significant type of test effect for the right ear ($p < .01$), with a better performance in the rapid test, but not for the left ear ($p = .87$). According to Cohen's classification system, the size of the ear effect was above "large" in the slow test ($d = 1.29$).

Discussion

The present results show a left-ear advantage in a task requiring discriminations of complex tones that were of identical pitch and overall intensity but differed in the shape of their amplitude envelopes. This advantage occurred both for rapid and slow amplitude variations, contrary to our expectation that a left-ear advantage would arise only when the amplitude variations were so rapid that they were likely to be analyzed in the frequency domain and not when they were so slow as to be perceived as changes of loudness over time. This expectation was based on the idea that the right-hemisphere superiority previously found for the perception of the temporal cues of timbre (Brancucci & San Martini, 1999; Samson & Zatorre, 1994; Samson, Zatorre, & Ramsay, 2002) was due to intensity variations' generating inharmonic spectral components that were processed in the frequency rather than the time domain. On the contrary, in this experiment, the left-ear advantage was even greater when the amplitude variations were too slow to generate relevant inharmonic spectral cues.

It may be noted that the ear advantage was greater when measured as reaction time rather than as number of errors. In fact, there was no ear advantage at all in terms of accuracy for the rapid test. We have no special explanation for this finding, though we may mention that the latter measure has also been shown to be less sensitive than reaction time in other dichotic studies on timbre perception (Brancucci & San Martini, 1999; Kallman & Corballis, 1975; Prior & Troup, 1988).

On the whole, the difference in laterality between the two tests confirms that different cortical mechanisms are involved in the perception of the two types of stimuli, but it runs contrary to the often mentioned dichotomy of right hemisphere–frequency domain versus left hemisphere–time domain. Whereas the left-ear superiority in the rapid test may still be accounted for by the notion of right-hemisphere superiority in the frequency analysis of sounds, for the left-ear advantage in the slow test, an explanation in terms of a frequency analysis of inharmonic residual spectral components seems implausible. That is, it may be argued that temporal variations are analyzed in the frequency domain as long as they are rapid enough to be of timbral interest and that otherwise they are processed in the time domain by different cortical mechanisms that may still be localized in the right hemisphere. Perceptual strategies that were unlikely to come into play in the rapid test may have played a role in the slow test. One might, for instance, consider that an essential aspect of the slow task was a computation of the relative durations of the rising and falling parts of the amplitude envelopes of the individual sounds. Such an operation requires fine timekeeping mechanisms, and these have been shown to be localized in the right, rather than left, hemisphere by various recent investigations (see Harrington & Haaland, 1999, for a review). For instance, in a study of patients with focal left and right hemisphere lesions produced by stroke, Harrington and collaborators (Harrington, Haaland, & Knight, 1998) required their participants to discriminate time intervals of around 300 and 600 ms between two successive tones. They found that, despite the similarity between the groups in lesion loci and size, only right-hemisphere damage was associated with a disruption of timekeeping operations when frequency discrimination and attentional processes were partialed out.

A second factor that might explain the left-ear advantage for the slow test could be that participants' performance critically depended on the ability to perceive intensity differences within tones. A right-hemisphere dominance for sound intensity discriminations in a condition of sustained attention was demonstrated by Belin and collaborators (Belin et al., 1998) in a study based on psychoacoustical and neuroimaging techniques. Their results suggest that discrimination of sound intensity involves two different right cortical networks: a supramodal frontoparietal network responsible for allocation of sensory attentional resources and a region of secondary auditory cortex specifically involved in sensory computation of sound intensity differences. It may be that, in the slow test condition, the critical aspect of the task responsible for the left-ear advantage was that it required computation of sound intensity differences within tones before intensity contours were compared.

There is another possible interpretation of the left-ear advantage for the slow test. It may be argued that temporal analysis of auditory tones, rather than being performed directly by the left hemisphere, must follow analysis of their static frequency and timbral characteristics in the right hemisphere. That is, one may reason that, if slowly fluctuating tones are first analyzed in the right hemisphere and then passed to the left hemisphere for temporal processing, a right-hemisphere advantage would arise because of the order in which these processes are performed. We note, however, that in the present experiment the presentation of the slow stimuli occurred in a separate session and was preceded by a familiarization phase. This allowed participants to become aware that the salient feature of the stimuli for the task was not their timbre or pitch, which were invariant, but only their intensity contour. In this situation, it seems unlikely that left-hemisphere processing of intensity fluctuations of stimuli presented to the contralateral ear is postponed until information about their timbre and pitch is transferred from the right hemisphere. Even so, only more direct methods of analysis of cortical activity could provide the last word on this issue.

In conclusion, the results of the present study fail to support our hypothesis that the advantage of the right hemisphere for intensity fluctuations is confined to rapid fluctuations that provide inharmonic spectral cues for the perception of timbre. Rather, they suggest an important role for the right hemisphere in the perception of temporal variations of intensity both when they are rapid and perceived as timbral qualities and when they are slow and perceived as changes of loudness over time.

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