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Gender differences in hemispheric asymmetry of syllable processing: Left-lateralized magnetic N100 varies with syllable categorization in females

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Abstract

The present study used magnetic source imaging to examine gender differences in the functional hemispheric asymmetry of auditory processing. The auditory evoked N100m was examined in male and female subjects in response to natural syllables with varying consonant and vowel as well as nonspeech noise. In an additional task subjects had to categorize different syllables from the first 35 ms of syllables, that is, the plosive and the formant transition. Syllable-evoked N100m activity was larger in the left than in the right hemisphere in female but not in male subjects. This gender-specific hemispheric asymmetry was speech specific, that is, absent when processing meaningless noise. Only in females did the degree of left-lateralization predict successful syllable categorization from short syllable bursts: Results suggest gender-specific differences in spectro-temporal analysis of speech.

Descriptors: N100, Magnetoencephalography, Speech, Gender, Differences, Syllable, Lateralization

Gender differences have been examined for various brain functions. In particular, differences in language functions have been discussed and related to faster development and more efficient functioning of the left cerebral hemisphere, which is dominant for language processing in most right-handed humans (Gur et al., 1999; Harasty, Double, Halliday, Kril, & McRitchie, 1997; Witelson, Glezer, & Kigar, 1995)—although the experimentally assessed degree of gender differences in performance varies in magnitude (Halpern, 1997; Hyde & Linn, 1988; McGuiness, Olson, & Chapman, 1990). In general, hemispheric asymmetry has been assumed to be more pronounced in male than in female subjects (Geschwind & Levitsky, 1968; Hellige, 1993; Kanno et al., 1998; Witelson & Kigar, 1992).

Because experimental evaluation of gender differences in hemispheric and performance asymmetry addressed different levels of language functions (from processing of syllables to verbal skills) gender-specific functional asymmetries and their relation to language processing remain to be clarified. The present study aimed at contributing to this clarification by examining gender-specific hemispheric asymmetries for consonant–vowel (CV) processing as a basic processing step in speech recognition comprising auditory spectro-temporal analysis.

Noninvasive imaging techniques such as functional magnetic resonance imaging (fMRI), high spatial resolution electroencephalography (EEG), or whole-head magnetoencephalography (MEG) allow the simultaneous recording from both hemispheres and therefore a direct assessment of functional hemispheric asymmetries. These methods disclosed lateralized processing of auditory stimuli with larger evoked responses contralateral to the stimulated ear (Eulitz, Diesch, Pantev, Hampson, & Elbert, 1995; Mäkelä et al., 1993; Pantev, Ross, Berg, Elbert, & Rockstroh, 1998; Rockstroh et al., 2001). Furthermore, lateralized responses to language stimuli like vowels and syllables (Eulitz et al., 1995; Poeppel et al., 1996) have been found. These results corroborated the hemisphere-specific representation of language functions and tested gender-specific hemispheric asymmetries. For instance, more pronounced left-hemispheric dominance in males than in females was found for passive listening to syllables (Rockstroh et al., 2001) whereas females displayed a stronger (left-lateralized) asymmetry when actively discriminating vowels (Obleser, Eulitz, Lahiri, & Elbert, 2001). Despite this evidence, a direct comparison of gender-specific lateralized processing and performance measures of speech decoding seems to be lacking.

The present study approaches possible gender differences in *functional* hemispheric asymmetry with two main questions: First, do gender-specific language functions become evident already on a very basic processing level like auditory spectro-

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temporal analysis? Spectro-temporal analysis is a prerequisite to categorize a spoken syllable and has been previously shown to activate mainly the left hemisphere (Schwartz & Tallal, 1980; Tallal, Miller, & Fitch, 1993; Zatorre, Evans, Meyer, & Gjedde, 1992), but is the functional asymmetry of the brain response to syllables also modulated by subjects' gender? Second, would a correlation between degree of lateralized auditory processing and actual performance in speech sound categorization allow us to relate functional asymmetry on this basic level of language function to performance, which potentially contributes to further stages of speech comprehension?

The prominent signature of cortical auditory processing, the N100m, served to index the processing of spoken syllables. It was hypothesized that female subjects show a left-hemispheric preponderance, that is, a left-lateralized N100m when attentively listening to syllables—similar to the reliable left-lateralized response to vowels previously found. Moreover, it was expected that the ability to discriminate consonant-vowel-syllables from the plosive and the formant transition only might be related to the degree of N100m lateralization. If so, this would support hemisphere- and gender-specific abilities for the spectro-temporal decoding of speech.

Materials and Methods

Participants

Twenty-two people (11 women, mean age 24.8 ± 3.3 years) gave written informed consent and were paid €20 for their participation. Subgroups (women and men) were matched for age (men 22–30 years, women 20–29 years) and education (all participants had 13 years of formal education). Participants were only included if they did not report any history of neurological, psychiatric, or otological illness. All participants were monolingual native speakers of German. Right-handedness was ascertained by the 10-item Edinburgh Handedness Questionnaire (Oldfield, 1971), and $(R-L)/(R+L)$ amounted at least to 90%. None of the participants reported left-handedness of their parents or siblings.

Stimulus Material

Naturally spoken German syllables were edited from recordings of words spoken by a female speaker.[1] Syllables were selected to combine a voiced stop consonants [b], [d], and [g] with either a FRONT rounded vowel [ø] or a BACK rounded vowel [o]. This resulted in six consonant–vowel syllables [bø], [dø], [gø], [bo], [do], and [go]. Speech signals were recorded with a Sennheiser™ MD-421 microphone on a DAT recorder and edited off-line. From the 20-kHz-digitized speech signal, 350-ms segments containing the plosive, the formant transition, and the steady-state vowel signal were cut out. Pitch frequency (279 ± 27 Hz, *M* ± *SD*) and formant frequencies varied within vowel categories for the six exemplars of each syllable category. The 36 stimulus audio files were faded out with 50-ms Gaussian ramps and normalized for peak amplitude. Stimuli were presented binaurally with 50 dB SL via a nonmagnetic echo-free stimulus delivery system with almost linear frequency characteristic in the critical range of 200–4000 Hz.

Experimental Design

Prior to the measurement, individual hearing thresholds were determined for both ears using 35-ms onset fragments separately for all six syllable categories. The final presentation sound pressure level was chosen according to the most insensitive hearing threshold, thereby guaranteeing at least 50 dB SL for all stimuli. Binaural loudness was slightly readjusted when necessary to ensure perception in the head midline.

In the subsequent *categorization task*, participants were asked to categorize the syllable from these onset fragments. Three onset exemplars of each syllable category were presented in a randomized sequence of 60 trials with a 3-s stimulus onset asynchrony. Participants indicated syllable identification on a list as forced choice. This behavioral task provides an index of fast speech sound discrimination ability, as the identification of the vowel only on the basis of the formant transition is difficult enough to minimize possible ceiling effects in discrimination performance. In the subsequent magnetoencephalography recording period, syllables were presented in full length (350 ms) and arranged in pseudorandomized sequences of 572 stimuli each with stimulus onset asynchrony varying around 1.8 ± 0.2 s. Each participant listened to three sequences while performing a *target detection task* in order to sustain a phonological processing mode: In every sequence, two syllables with a lowered cumulated probability of 10% served as targets (e.g., [bo] and [dø]). Participants were asked to press a button with their right index finger upon target detection. Across the three sequences, all six syllable categories constituted targets.

The recording session ended with a passive listening *noise condition* with 150 trials of a bandpassed noise stimulus. This test served as a nonverbal functional landmark of belt area activation in primary auditory cortex (Kaas, Hackett, & Tramo, 1999; Wessinger et al., 2001). A 350-ms white noise probe (5 ms onset, 50 ms Gaussian offset ramps) was bandpass filtered (center frequency 1 kHz, width 0.3 oct) and was also presented binaurally at 50 db SL with a randomized stimulus onset asynchrony of 1.8 ± 0.2 s. The noise stimulus presentation sound pressure level was exactly the same as in the syllable runs. The noise audio file exhibited the same root mean square sound pressure level as the average syllable audio file.

As in previous studies (Obleser et al., 2001; Obleser, Elbert, Lahiri, & Eulitz, 2003; Obleser, Lahiri, & Eulitz, 2004), participants were allowed to watch silent videos during magnetoencephalographic recording in order to maintain constant alertness and to reduce excessive eye movements.

Data Acquisition and Reduction

Magnetoencephalograms were recorded using a whole-head neuromagnetometer (MAGNES 2500, 4D Neuroimaging, San Diego, CA) in a magnetically shielded room (Vaccumschmelze, Hanau, Germany). Before the measurement, participants' head shape was digitized using a fast digitization stylus (Fastrak, Polhemus, Colchester, UK).

Auditory evoked fields were determined from 800-ms epochs (including a 200-ms pretrigger baseline) that were recorded with a bandwidth from 0.1 to 100 Hz and a 687.17 Hz sampling rate. Epochs with the peak-to-peak amplitude exceeding 3.5 pT in one of the channels or with the coregistered EOG signal exceeding 100 μV were rejected. Epochs with targets and epochs with false-positive button presses were also excluded. The resulting 250 artifact-free epochs on average for every subject and syllable category were averaged after off-line noise correction. A 20-Hz

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[1] As previous studies with synthetic male (Obleser et al., 2001), natural male (J. Obleser, A. Lahiri, & C. Eulitz, unpubl. data), or female voices (Rockstroh et al., 2001) did not suggest a crucial impact of the speaker's voice on brain responses, we decided not to extend the design and double the sample size by balancing the speaker gender.

low-pass filter (Butterworth 12 dB/oct, zero phase shift) was subsequently applied to the average. Noise condition trials were analyzed in the same way as the syllable conditions.

The N100m component was defined as the peak in the time range between 90 and 160 ms (Figure 1). For analysis of the N100m component, an equivalent current dipole (ECD) in a spherical volume conductor (fitted to the shape of the regional head surface) was modeled at every sampling point separately for the left and the right hemispheres (Obleser et al., 2001, 2003, 2004; Sarvas, 1987). The three best successive dipole solutions in the rising slope of the N100m were chosen to determine source parameters: The resulting median dipole solution represents the center of gravity for the massed and synchronized neuronal activity. Dipoles were selected when they met the criteria of goodness of fit greater than .95 and 95% confidence volume smaller than 300 mm^3. N100m asymmetry was evaluated by root mean square amplitude, source strength and the laterality index. Laterality index was defined as the ratio of (source strength$_{\text{left}}$ − source strength$_{\text{right}}$) to (source strength$_{\text{left}}$ + source strength$_{\text{right}}$) with positive values indicating lateralization to the left (Obleser et al., 2001; Rockstroh et al., 2001).

Statistical Analyses

Effects of gender, hemisphere, and syllable category on the N100m amplitude, latency, and location were analyzed for the root mean square peak latency and the N100m source strength (as well as location in posterior–anterior, medial–lateral, and inferior–superior dimension) in analyses of variance (ANOVA) with the between-subjects factor Gender (male, female) and the within-subjects factors Hemisphere (left, right), and Syllable ([bø], [dø], [gø], [bo], [do], [go]). ANOVA of the laterality index of the source strength included the factors Syllable and Gender. Effect sizes of potential gender main effects were calculated using Cohen's *d*. Violation of the sphericity assumption (Picton et al., 2000) was considered using Mauchly's criterion for all significance tests including the factor Syllable.

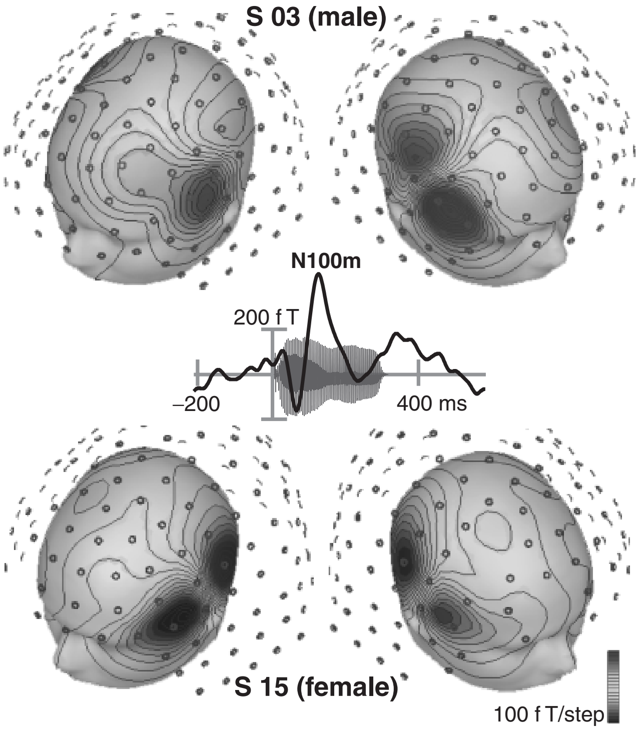

Figure 1. A typical auditory evoked response to the syllable [bo] from an exemplary channel is shown (middle) superimposed on the oscillogram of a [bo] waveform. The N100m is the most prominent response, appearing approximately 100 ms after syllable onset. The field distribution of the N100m peak is shown for a male (upper panel) and a female subject (lower panel). Note the left-hemispheric differences. For illustration, magnetoencephalographic sensor space data have been projected onto a schematic head surface.

Results

Performance

Subjects accomplished the categorization task of the 35-ms syllable onsets well above chance level (Figure 3). Including all six response options reduced chance level to 16.67%. Subjects responded correctly in 76 ± 3.6% of the 60 test items. Target detection in the target detection task during magnetoencephalographic recording was accomplished with an average 89.7 ± 1.6% correct button presses. Male and female subjects did not differ significantly in any of the behavioral measures (number of errors in the *categorization task*, false alarm button presses, and misses in the *target detection task*; one-way ANOVAs with the factor Gender).

Brain Magnetic Responses

An N100m (Figure 1) was found in each hemisphere and in every subject. N100m peak latency was similar in male (105 ms) and female subjects (109 ms, n.s.). However, magnetic source imaging is highly dependent on the dipolarity of the evoked magnetic field, and demands an excellent signal-to-noise ratio. In the approach we used, satisfying source solutions for six syllable categories, one bandpassed noise category and two hemispheres had to be accomplished. If only one condition failed, statistical analysis of this subject's data was not suitable anymore. Hence, comprehensive sets of single equivalent current dipole models for the N100m in both hemispheres could be fitted only in 16 subjects (8 women). The 95% confidence volume of the source amounted to 151 mm^3 (male subjects 161 mm^3, female subjects 141 mm^3, n.s.). Source location along posterior–anterior, medial–lateral, or inferior–superior dimension also did not differ between male and female subjects.[2] The average goodness of fit of the dipole solutions was 0.97 ± 0.16. Goodness of fit was somewhat better in female subjects in the left hemisphere (indicating a stronger dipolarity of the field distribution: Goodness of fit$_{\text{left}}$ = .977, Goodness of fit$_{\text{right}}$ = .958), whereas male subjects showed a reverse pattern (Goodness of fit$_{\text{left}}$ = .961, Goodness of fit$_{\text{right}}$ = .972, Hemisphere × Gender $F(1,14) = 5.56, p < .05$). Analysis of the source strength reflecting the synchronized neuronal activity revealed a Gender × Hemisphere interaction, $F(1,14) = 6.29$, $p < .03$ (Figure 2). This effect resulted from a left-lateralized activity in female subjects ($\Delta_{\text{source strength}} = 13.0$ nAm, $F(1,7) = 10.8$, $p < .01$), whereas male subjects showed no lateralization ($\Delta_{\text{source strength}} = -2.5$ nAm, $F < 1$). A main effect of Gender for the laterality index, $F(1,14) = 6.59$, $p < .03$, confirmed this result (female subjects laterality index = +.25, male subjects laterality index = −.06; Figure 3). The effect size of this difference in laterality amounted to $d = 1.27$.

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[2] Effects of the different syllable categories on auditory processing did not interact with Hemisphere or Gender whatsoever and are reported separately (Obleser, Lahiri, & Eulitz, 2003).

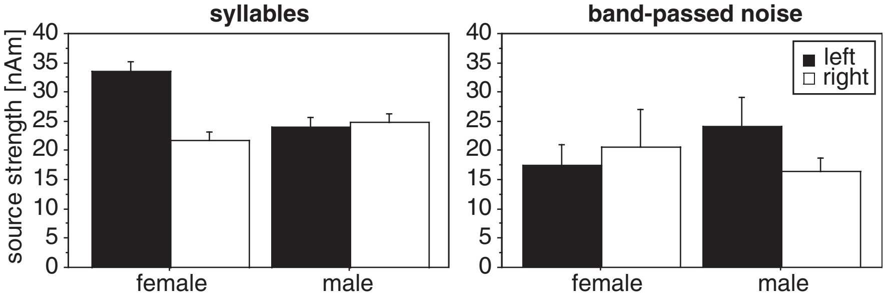

Figure 2. Means ± *SEM* of source space amplitudes are shown separately for female and male subjects in the left (black bars) and right hemispheres (white bars). Left panel (syllables): compared to the relative left-hemispheric preponderance in women, no imbalance is evident for men, which explains the Gender × Hemisphere interaction. Right panel (bandpassed noise): the analogue means distribution for amplitudes to nonspeech noise shows no such interaction.

Comparison of Speech and Noise Processing

N100m asymmetry was compared between the mean activity across all six syllable categories and the noise condition in an ANOVA including the within-subject factors Condition (noise, syllable), Hemisphere (left, right) and the between-subject factor Gender. A significant Gender × Hemisphere × Condition interaction for the source strength confirmed the left-lateralization in female subjects to be speech specific, $F(1,16) = 5.07$, $p < .05$: Only syllables produced the laterality difference between male and female subjects ($p < .03$, see above; Figure 2), whereas N100m to noise stimuli did not differ significantly between hemispheres, $F < 1$, or gender, $F < 1$, Gender × Hemisphere interaction $F = 1.87$, n.s.

Correlation between Behavioral Measures and Auditory Evoked Fields

Although all subjects accomplished the *categorization task* from the first 35 ms of the stimuli equally well, the extent of left-lateralized N100m correlated significantly with performance only in females ($r = .75$, $p < .03$), but not in males ($r = -.49$; Figure 3).

Discussion

In a previous study (Obleser et al., 2001), we have reported that the functional asymmetry of the auditory evoked field in response to vowels differed between male and female subjects. The present study extended this finding to the lateralized processing of consonant-vowel-syllables. Furthermore, a comparison with the processing of a nonspeech control condition was included, and the correlation of the functional asymmetry of auditory evoked fields and subjects' performance in categorizing consonant-vowel-syllables was studied.

Two main results of this study deserve discussion: First, female subjects displayed a left-lateralized brain activity in the time window of the N100m response, in contrast to male subjects, who showed no hemispheric preponderance. This adds to the results of gender-specific lateralization in vowel processing mentioned above. This gender difference may be speech specific, as it was absent during processing of nonverbal noise bursts. Second, the extent of lateralization to the left was positively correlated with female subjects' ability to correctly categorize the syllables from the first 35 ms of stimuli only.

Results on gender-specific hemispheric asymmetries related to language functions are inconsistent. Some studies found more left-lateralization in female than male subjects (e.g., Inglis, Ruckman, Lawson, MacLean, & Monga, 1982; Obleser et al., 2001) or stronger right-lateralization in males (Meinschaefer, Hausmann, Güntürkün, 1999), whereas others either did not find gender differences (e.g., Frost et al., 1999; Knecht et al., 2000) or even reported stronger asymmetry in males (Rockstroh et al., 2001; Shaywitz et al., 1995). A morphometric basis of gender differences in language-related hemispheric asymmetry may be derived from a stronger leftward asymmetry of the planum temporale in girls (Preis, Jänke, Schmitz-Hillebrecht, & Steinmetz, 1999), although this gender difference is not consistently reported (Kulynych, Vladar, Jones, & Weinberger, 1994).

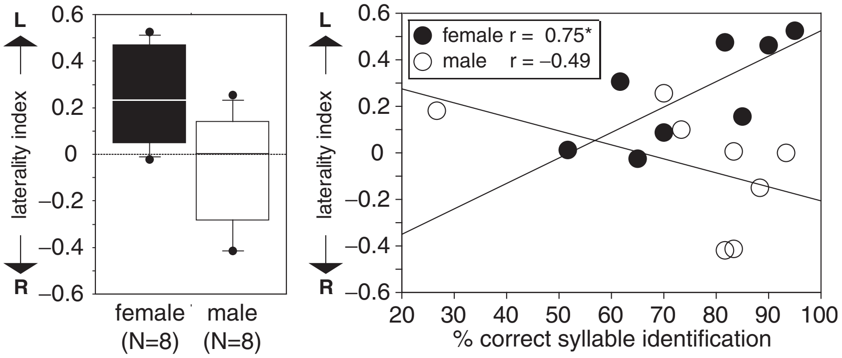

Figure 3. On the left, distribution of the source strength laterality index is shown for female (black) and male (white) subjects. On the right, correlations between this laterality index and performance in categorization of syllables from the onsets only is shown for female (black) and male (white) subjects separately. *$p < .05$. Note that better performance (abscissa) was accompanied by stronger left-lateralization (ordinate) in female subjects.

Differences across studies may further result from variable experimental designs, including effects of task, stimulus complexity, or physical aspects. With respect to task effects, passive listening (as employed by Rockstroh et al., 2001) may challenge hemisphere-specific processing less than active processing—as used in the present study—which therefore may enhance functional hemispheric asymmetry (Poeppel et al., 1996). Similarly, Hertrich, Mathiak, Lutzenberger, and Ackermann (2002) reported a lateralization effect to the left for the auditory mismatch negativity, whenever attention had to be directed toward the channel, to which synthetic auditory consonant-vowel events were presented, and whenever visual distraction made the processing of natural consonant-vowel events in an oddball design more demanding. These results suggest that more demanding tasks to the subjects may be a prerequiste to make functional asymmetries in processing of speech sound visible.

Experimental designs also vary with respect to the level of language processing under investigation. It seems possible that lateralized processing is confined to basic steps in speech processing at the acoustic/phonetic level, whereas the processing of semantic or syntactic information involves networks in both hemispheres. The N100m component mirrors comparably low-level processing stages, such as decoding of formant transitions, and reflects auditory pattern recognition and integration (Näätänen & Winkler, 1999). Other experimental approaches studying acoustic/phonetic processing of speech delivered similar laterality effects as reported here: Hertrich et al. (2002) used the auditory mismatch negativity to examine the impact of temporal resolution of acoustic events on lateralized processing. They found increasing left-hemispheric mismatch negativity subsequent to left-ear synthetic deviants in female subjects about 200 ms after stimulus onset in contrast to male subjects.

On the other hand, males displayed a larger left-hemispheric preponderance in experimental language tasks involving higher level processing stages like word recognition (Walla, Hufnagl, Lindinger, Deecke, & Lang, 2001), phonological rhyme-matching (Coney, 2002; Shaywitz et al., 1995), or semantic categorical decision making in the visual domain (Shaywitz et al., 1995). No gender differences were found in more complex language tasks like word generation (Knecht et al., 2000) or semantic categorization in the auditory modality (Frost et al., 1999).

Experimental designs also vary with respect to physical stimulus characteristics, natural versus synthetic syllables, or same-sex versus opposite-sex voice of the speaker. We found similar differences in lateralization between female and male subjects, whether stimuli were produced by a synthetic male-sounding voice (Obleser et al., 2001, $d = 1.36$) or a natural male voice (J. Obleser, A. Lahiri, & C. Eullitz, unpubl. data; $d = 1.47$). But it might be argued that the perception of the same-sex voice activates language-related networks more intensively than perceiving an opposite-sex voice: Supposing that the activation of speech processing networks in adults results from learning and experience, one might assume that both male and female speakers hear far more their own voices, that is, same-sex speech than opposite-sex speech. Future studies are necessary to finally rule out an effect of the sex of speaker's voice on the described lateralization pattern; however, the coherent effect sizes across different studies argue against this possibility.

Moreover, the missing lateralization in the nonspeech control condition was used to argue for the speech specifity of the lateralization difference during syllable processing. However, one should be aware that the nonspeech noise condition was recorded in an extra recording block, using a passive listening task instead of active processing with no variability across stimuli. The presentation of noise bursts was separated from the syllable conditions to avoid perceptual pop-out effects, which themselves could have elicited differential brain responses. The major purpose of the control condition was to have a functional landmark to relate the location of the syllable sources to well-known parts of the auditory cortex active during noise perception. An upcoming study should scrutinize the interplay of attentional demands and hemispheric laterality. The missing Gender × Hemisphere interaction in response to nonspeech noise is at least an important hint toward a stimulus dependency of hemispheric asymmetry during auditory perception.

The second noteworthy result of the present study was the correlation between the extent of lateralization to the left and the ability to categorize the syllables correctly from the first 35 ms of stimuli. This correlation was significant only in female subjects, although overall performance was similar in both gender groups. This suggests either that female subjects need more activation of left-hemispheric language-specific networks to analyze auditory pattern whereas males accomplish the same task with the same outcome by activating basic auditory processing networks both in the right and the left hemisphere (Hertrich et al., 2002; Zatorre, Belin, & Penhune, 2002) or that an advantage in left-hemispheric spectro-temporal processing favors accurate speech decoding. Nonetheless, categorization performance certainly involves more aspects of linguistic processing than just spectro-temporal analysis of the speech signal. But the basic mechanisms of spectro-temporal processing comprise a prerequisite to further language processing and may therefore crucially influence these subsequent steps.

In sum, this study

1. extends previous results of early left-hemispheric lateralization in female subjects when they actively process basic speech material (Obleser et al., 2001);
2. relates a greater extent of left-hemispheric processing in females to better auditory categorization, whereas male subjects did not show such a correlation; and
3. suggests left-hemispheric preponderance for spectro-temporal processing and a female superiority in focusing on this basic aspect of speech.

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