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Research Paper

EEG rhythms lateralization patterns in children with unilateral hearing loss are different from the patterns of normal hearing controls during speech-in-noise listening

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ABSTRACT

Unilateral hearing loss constitutes a field of growing interest in the scientific community. In fact, this kind of patients represent a unique and physiological way to investigate how neuroplasticity overcame unilateral deafferentation by implementing particular strategies that produce apparently next- to- normal hearing behavioural performances. This explains why such patients have been underinvestigated for a long time. Thanks to the availability of techniques able to study the cerebral activity underlying the mentioned behavioural outcomes, the aim of the present research was to elucidate whether different electroencephalographic (EEG) patterns occurred in unilateral hearing loss (UHL) children in comparison to normal hearing (NH) controls during speech-in-noise listening. Given the intrinsic lateralized nature of such patients, due to the unilateral side of hearing impairment, the experimental question was to assess whether this would reflect a different EEG pattern while performing a word in noise recognition task varying the direction of the noise source. Results showed a correlation between the period of deafness and the cortical activity asymmetry toward the hearing ear side in the frontal, parietal and occipital areas in all the experimental conditions. Concerning alpha and beta activity in the frontal and central areas highlighted that in the NH group, the lateralization was always left-sided during the Quiet condition, while it was right-sided in noise conditions; this evidence was not, however, detected also in the UHL group. In addition, focusing on the theta and alpha activity in the frontal areas (Broca area) during noise conditions, while the activity was always left-lateralized in the NH group, it was ipsilateral to the direction of the background noise in the UHL group, and of a weaker extent than in NH controls. Furthermore, in noise conditions, only the UHL group showed a higher theta activity in the temporal areas ipsilateral to the side where the background noise was directed to. Finally, in the case of bilateral noise (background noise and word signal both coming from the same two sources), the theta and alpha activity in the frontal areas (Broca area) was left-lateralized in the case of the NH group and lateralized towards the side of the better hearing ear in the case of the UHL group.

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Taken together, this evidence supports the establishment of a particular EEG pattern occurrence in UHL children taking place in the frontal (Broca area), temporal and parietal lobes, probably physiologically established in order to deal with different sound and noise source directions.

1. Introduction

After many years of underinvestigation, due to next to normal behavioural performances, unilateral hearing loss (UHL) patients have become a subject of research, to investigate how neuroplasticity coped with and (presumably) overcame unilateral deafferentation. If such patients are intrinsically “lateralized”, how would this condition fit with the achievement of the typical left hemisphere specialization for linguistic functioning, attained only once early critical stages of learning are completed (Stiles et al., 2005)? The hemispheric specialization for language originated from the legendary studies by the neurosurgeon Wilder Penfield and colleagues, who in the 1930s electrically stimulated areas of the cerebral cortex, providing an electrical mapping of brain functions (Purves et al., 2009). More recently, it has been shown that such specialization of the left hemisphere is subjected to modulation by the extent of availability of the auditory information embedded into the auditory stimulus (i.e. a left anterior temporal pathway for speech comprehension, which is active only in the case of intelligible speech stimuli) (Scott et al., 2000). These results are closely related to the study of the listening effort in humans, since under more challenging listening conditions the “typical” auditory network engages additional areas also in the contralateral hemisphere (Talavage et al., 2014). Listening effort is defined as “deliberate allocation of mental resources to overcome obstacles in goal pursuit when carrying out a listening task” (Pichora-Fuller et al., 2016). It has been shown that auditory conditions producing listening effort, like speech in noise, spectrally degraded speech and linguistic complexity, produce an increase in the cerebral activity recorded at the level of the prefrontal cortex regions (for a meta analysis Alain et al., 2018). Specifically, functional magnetic resonance imaging (fMRI) studies showed that several regions are involved for accurate speech-in-noise processing, supporting the presence of a wider network in the case of difficult listening conditions. Moreover, areas involved in sensorimotor integration seem to be recruited as the difficulty in speech in noise perception increases, with dorsal areas (e.g. Broca area and ventral premotor cortex) being increasingly engaged with increasing task difficulty and ventral brain regions (e.g. anterior superior temporal gyrus and anterior middle temporal gyrus) decreasing their activity (Du et al., 2014). In fact, the same researchers (Du et al., 2014) observed a higher specificity in NH participants of the activity in the left ventral premotor cortex and Broca area for phoneme categorization under high background noise level conditions, instead of bilateral auditory cortices; these latter were instead more involved when the signal-to-noise ratio (SNR) was extremely weak (SNR > 8 dB).

Besides self-reports and cognitive-behavioural measures, also electroencephalography (EEG) has been used in the attempt to measure listening effort. Alpha rhythm (approximately 8–13 Hz) has been observed to decrease during active processing of language stimuli (Klimesch et al., 2007) and, more in particular, for alpha a “gating by inhibition” mechanism has been hypothesized, aimed at inhibiting task-irrelevant activities in task-irrelevant regions (Jensen and Mazaheri, 2010). Instead, gamma band (approximately 30–100 Hz) synchronization and simultaneous alpha band desynchronization would mark active processing in engaged areas (Jensen and Mazaheri, 2010). Similarly, an anticipatory/preparatory role of alpha prior to the arrival of an anticipated stimulus has been suggested (Foxe and Snyder, 2011). According to thisWeisz and colleagues (Weisz et al., 2011) supported the role of alpha for the maintenance of the activation-inhibition balance, constituting the main rhythm at rest and desynchronizing when anticipating or processing a stimulus (Thut et al., 2006). Specifically, the extent of the alpha activity suppression influences the resulting speech intelligibility (Obleser and Weisz, 2012). Moreover, evidence showed alpha increases in central–parietal (Obleser et al., 2012; Petersen et al., 2015) and occipital-parietal (Wisniewski et al., 2017) areas, depending on acoustic degradation (higher alpha power with more severe acoustic degradation). Accordingly, in asymmetric sensorineural hearing loss children, the investigation of the phase preceding the expected stimulus showed an increase in parietal alpha power levels under more difficult auditory task conditions (Marsella et al., 2017). In addition to alpha, also theta (approximately 4–8 Hz) power variation reflects varying difficulties of listening conditions. For theta activity, a role in working memory and lexico-semantic processing has been highlighted (Strauβ et al., 2014; Wisniewski et al., 2015). Furthermore, data from noise-vocoded speech experiment have revealed that theta power increases in frontotemporal channels at the presentation of more acoustic details (Obleser and Weisz, 2012), that is to say with increasingly available auditory information to be processed.

As regards the hearing-impaired population, alpha and theta rhythms as indices of listening effort in a word-in-noise recognition task under different signal and noise directions have already been investigated in children who are candidates for cochlear implant (CI) surgery (Cartocci et al., 2015) and in adult unilateral CI users (Cartocci et al., 2018), but also in the comparison of CI processors to identify the device and functions allowing less effortful listening (Cartocci et al., 2016a,b).

A study in normal hearing (NH) participants that extended the investigation of language (sentence) processing also to beta (approximately 13–30 Hz) and gamma band activity showed a left-lateralized activity for all the EEG rhythms examined (Lam et al., 2016).

Beta activity has been mainly related to motor activities (Sauseng and Klimesch, 2008), although a role in the fronto-parieto-temporal attentional network communication (Gross et al., 2004) and, concerning more specifically the auditory neuroscience field, during auditory-motor rhythm learning tasks a beta synchronization was observed, especially in late stages of learning (Edagawa and Kawasaki, 2017). Furthermore, Spironelli and Angrilli (2010) showed a particular role for beta (high beta) band as a marker of acquired language left hemispheric dominance both in children and adults.

Gamma power has been shown to increase when the integration in the semantic context was facilitated (Obleser and Kotz, 2011) and, specifically, this increase was observed in the left temporal cortex coinciding with correctly identified words among degraded speech signals (Hannemann et al., 2007).

Summarizing the relationship between EEG rhythm studies and language processing, an involvement of theta, alpha, beta and gamma rhythms has been suggested in language processing (Lam et al., 2016), expanding the concept of the only involvement of a "core" language network (i.e. left perysilvian cortex), but also additional networks, located such as in the temporal cortex for the memory network and in the right parieto-frontal cortex for the attentional network. Indeed, a systematic scheme regarding the interplay among regions involved in language processing has been provided by Fedorenko and Thompson-Schill (2014).

The aim of the present study is to compare EEG lateralization patterns in UHL in comparison to NH children in different SNR configurations. In relation to this we make the following hypotheses:

1. the unilateral hearing loss (UHL) group present a differential lateralization EEG pattern in comparison to normal hearing (NH) children in response to varying signal and noise directions, mirroring different neural strategies adopted by the brain in order to deal with the one-side deafferentation
2. the presumably most difficult condition for UHL children is the one with the noise directed towards the hearing ear and frontal signal; this is reflected by particular EEG patterns in this condition, even if different behavioural performances are not necessarily expected.

2. Material and methods

2.1. Participants

All participants and participants' parents were given detailed information about the study and signed an informed consent form. Participants were volunteers, who did not receive any compensation for taking part in the study. The experiment was performed in accordance with the principles outlined in the Declaration of Helsinki of 1975, as revised in 2000, and it was approved by the institutional Ethics Committee (Protocol: 705/FS).

Participants were divided into a normal hearing (NH) control group ($n = 12$; 6f, 6 m; age: $12 \pm 2{,}4863$) and a unilateral hearing loss (UHL) group ($n = 13$; 6f, 7 m; age: 10 ± 2198) (Table 1 for further details), characterized by profound deafness in one ear (average threshold for pure tone frequencies 250–4000 Hz $\geq$ 90 dB HL) and normal hearing in the contralateral ear (average threshold for pure tone frequencies 250–4000 Hz $\leq$ 20 dB HL).

2.2. Experimental protocol

Participants performed a forced-choice word recognition task, in which stimuli consisted of Italian disyllabic words from "Audiometria Vocale GNResound" (Turrini et al., 1993), delivered free-field at an intensity of 65 dB SPL, measured at the subject's head. Continuous 4-talker babble background noise was used as the competing signal in order to provide informational masking (masking containing semantic information strongly interfering with the linguistic processing of the target). The experimental conditions were: Quiet condition and three background noise configurations that have already been used in previous studies (Cartocci et al., 2018; G. Cartocci et al., 2015; Ching et al., 2009; Kokkinakis and Pak, 2014; Marsella et al., 2017), where the competing noise was delivered: i) frontal bilaterally, that is from two loudspeakers placed at +45° and −45° in relation to the participant; ii) at an angle of +90° from the frontal signal; iii) at an angle of −90° from the frontal signal. During EEG recordings, the SNR was kept constant at +10, with the noise intensity delivered at 55 dB SPL.

The protocol has already been employed in previously published studies involving cochlear implant candidates (Cartocci et al., 2015) and cochlear implant users (Cartocci et al., 2018; Marsella et al., 2017). Before exposure to the experimental stimuli, participants were asked to look at a black screen for 60 s, and the EEG activity recorded during this "open-eye condition" was then used for the IAF calculation (Goljahani et al., 2012). Each experimental condition (Quiet and noise conditions) comprised 20 trials, corresponding to 20 words randomly delivered, and each trial consisted of 4 phases: Pre-Word (the phase preceding the onset of the target words), Word (the phase corresponding to the listening of the target words), Pre-Choice (the phase preceding the request of a response from the participant) and Choice (the phase in which the participant had to choose and press one out of four coloured buttons on a customized key-board, in order to select the just-heard word stimulus among four words, each appearing in a different coloured box on the screen). The target word had a 25% probability of appearing in one of the four coloured boxes and positions on the screen (top left, bottom left, top right, bottom right). The former three phases lasted 1 s, while the Choice phase lasted a maximum of 5 s, depending on the response time, resulting in a trial with a maximum 8-s total length.

2.3. EEG signal acquisition and processing

A digital ambulatory monitoring EEG system (Bemicro EBNeuro, Italy) was used to record the 19 channels (Fp1, Fp2, Fz, F3, F4, F7, F8, Cz, C3, C4, T3, T4, Pz, P3, P4, T5, T6, O1, O2), with a sampling frequency of 256 Hz. The impedances were maintained below 10 kΩ, and a 50- Hz notch filter was applied to remove the power interference. A ground and a reference electrode were placed on the forehead. The EEG recording was filtered with a 4th order Butterworth band pass filter (1–40 Hz), so as to reject continuous

Table 1
Demographic and clinical data of the unilateral hearing loss (UHL) group.

UHL patients	Age	Sex	Side of deafness	Etiology	Period of deafness
B.E.	10	M	left	Congenital cytomegalovirus	Since birth
C.A.	8	M	right	Unknown	Unknown, > 4 years
C.M.	9	F	right	Unknown	Unknown, > 1 year
D.P.E.	9	F	right	Unknown	Unknown, > 5 years
A.N.H.	9	M	right	Unknown	Unknown, > 3 years
G.M.	10	M	left	Unknown	Since birth
P.B.	8	F	left	Unknown	Since birth
T.C.	15	M	right	Sudden sensorineural hearing loss/Labyrinthitis	1 year
M.A.	10	F	right	Unknown/Labyrinthitis	2 years
P.F.	14	M	left	Unknown	8 years
P.S.	11	F	right	Unknown	Since birth
C.V.	9	F	right	Unknown	Since birth
D.R.D.	8	M	left	Sudden sensorineural hearing loss from enlarged vestibular aqueduct	19 months

components as well as high-frequency interferences, like muscular artefacts. The Fp1 channel was used to remove eye-blink contributions from each channel of the EEG signal by using the REBLINCA algorithm (Di Flumeri et al., 2016). This method makes it possible to correct the EEG signal without losing data. For other sources of artefacts, specific procedures of the EEGLAB toolbox (Delorme and Makeig, 2004) were employed. Firstly, the EEG signal was segmented into epochs of 2 s (Epoch length) shifted by 0.125 s (Shift). This windowing was chosen with the compromise of having both a high number of observations, in comparison with the number of variables, and to respect the condition of stationarity of the EEG signal (Elul, 1969). In fact, this is a necessary assumption in order to proceed with the spectral analysis of the signal. The EEG epochs with the signal amplitude exceeding $\pm 100\,\mu V$ (*Threshold criterion*) are marked as “artefact”. Each EEG epoch is thus interpolated in order to check the slope of the trend within the considered epoch (*Trend estimation*). If such a slope is higher than $10\,\mu V/s$, the considered epoch is marked as “artefact”. Finally, the signal sample-to-sample difference (*Sample-to-sample criterion*) was analysed: if such a difference, in terms of absolute amplitude, is higher than $25\,\mu V$, i.e. an abrupt variation (non-physiological) occurred, the EEG epoch is marked as “artefact”. At the end, the EEG epochs marked as “artefact” were removed from the EEG dataset in order to have a clean EEG signal to perform the analyses (Aricò et al., 2017; Borghini et al., 2017). In order to consider any subjective difference in terms of brain rhythms, for each participant the Individual Alpha Frequency (IAF) was computed on the 60-s-long Open Eyes segment (Goljahani et al., 2012), recorded at the beginning of the experimental task, in order to define the EEG bands of interest. Each band was then defined as “IAF ± x”, where IAF was the Individual Alpha Frequency, in Hertz, and x an integer in the frequency domain (Klimesch, 1999). Thus, the EEG activity was divided, by filtering the EEG signals in the following frequency bands: theta [IAF-6 ÷ IAF-2 Hz], alpha [IAF-2 ÷ IAF+2 Hz], beta [IAF+2 ÷ +IAF+16 Hz] and gamma [IAF+16 ÷ +IAF+30 Hz]. The EEG recordings were then segmented into trials, corresponding to each word of each experimental condition (Quiet, Bilateral Noise, Noise +90°, Noise −90°). The Power Spectrum Density (PSD) was calculated in correspondence of the different conditions with a frequency resolution of 0.5 Hz.

2.4. Lateralization index

With the aim of investigating the lateralization between hemispheres in the response to varying background noise directions, an index of lateralization was employed between the two cerebral hemispheres' activity. The Lateralization Index (LI) was calculated on the basis of the formula previously adopted by Vanvooren and colleagues (Vanvooren et al., 2015):

$$LI = \frac{R - L}{R + L}$$

Where R stands for right hemisphere and L for left hemisphere. In fact, this index measures the extent of the lateralization to a specific hemisphere. The LI ranges from +1, for cortical activity entirely asymmetrical to the right hemisphere, to zero for symmetrical cortical activity, and −1 for cortical activity entirely asymmetrical to the left hemisphere.

The above-mentioned researchers (Vanvooren et al., 2015) applied the LI on NH participants, while in the present study it was calculated on the NH group but was modified for the UHL patients, in order to make it suitable for their peculiar audiological features, consisting of one hearing ear and one deaf ear. Therefore the adopted LI formula for the UHL group was the following:

$$LI = \frac{Hearing\ Ear\ Side - \ Deaf\ Ear\ Side}{Hearing\ Ear\ Side + \ Deaf\ Ear\ Side}$$

In this case the LI thus ranged from +1, when the cortical activity was completely asymmetrical to the hearing ear side, to −1, when the cortical activity was completely asymmetrical to the deaf ear side.

The LI was calculated for each pair of analogue electrodes in the two hemispheres (e.g. T3-T4, F3-F4, etc.).

2.5. Statistical analysis

The Shapiro-Wilk normality test was first applied to the variables under investigation. Depending on the result of the normality test, parametric or non-parametric ANOVA (Friedman ANOVA) was used within each group (NH and UHL) in order to investigate statistical differences among the experimental conditions (4 levels): Quiet, Bilateral Noise, Noise to Right Ear, Noise to Left Ear − in the case of the UHL group, Noise to Right Ear and Noise to Left Ear conditions were replaced by Noise to the Hearing Ear and Noise to the Deaf Ear. Similarly, ANOVA and non-parametric ANOVA (Kruskal Wallis ANOVA) were employed for the comparison between groups among the lateralized noise conditions (Noise to Right Ear, Noise to Left Ear, Noise to the Hearing Ear and Noise to the Deaf Ear). The post hoc test (Holm-Bonferroni test for non parametric analysis and Duncan's test for parametric analysis) was then applied to statistically significant interactions in order to perform pairwise comparisons. The unpaired *t*-test or Mann-Whitney *U* test was used in the comparison between the groups in the Quiet and Bilateral Noise condition. Linear regression analysis was conducted to investigate any correlation between behavioural performances and period of deafness (years) and relevant EEG data.

3. Results

3.1. Behavioural results

The comparisons within each experimental group showed a difference among the conditions for the UHL group (Friedman ANOVA Chi Sqr. $(N = 12, df = 3) = 25.417$ $p < 0.001$) (Fig. 1 left), but not for the NH group (Friedman ANOVA Chi Sqr. $(N = 12, df = 3) = 3.235$ $p = 0.357$) (Fig. 1 right). In particular, in the UHL group the condition that produced the highest number of errors was the Noise to the Hearing Ear condition, which was also the condition that produced the highest percentage of errors also in relation to the NH group.

No statistically significant correlations ($p > 0.05$) were found between the percentage of errors in the Noise to the Hearing Ear and Noise to the Deaf Ear experimental conditions and the LI values obtained in the theta and alpha bands in temporal and frontal areas (these areas and EEG bands were investigated for the correlation analysis since they showed a particular pattern in the UHL group, please see below in the text for more details).

3.2. Theta band

Concerning the UHL group, a statistical significance was found for the T3-T4 (Friedman ANOVA Chi Sqr. $(n = 13, df = 3) = 8.723$ $p = 0.033$), in particular the Noise to the Deaf Ear condition showed a statistically significant difference from the Quiet condition ($p = 0.004$) (Fig. 2 left), and for the T5-T6 (ANOVA $F(3, 36) = 4.385$ $p = 0.01$), with the Noise to the Deaf Ear condition reporting different LI values in comparison to the Quiet ($p = 0.022$) and the Noise to the Hearing Ear condition ($p = 0.002$) (Fig. 2 centre)

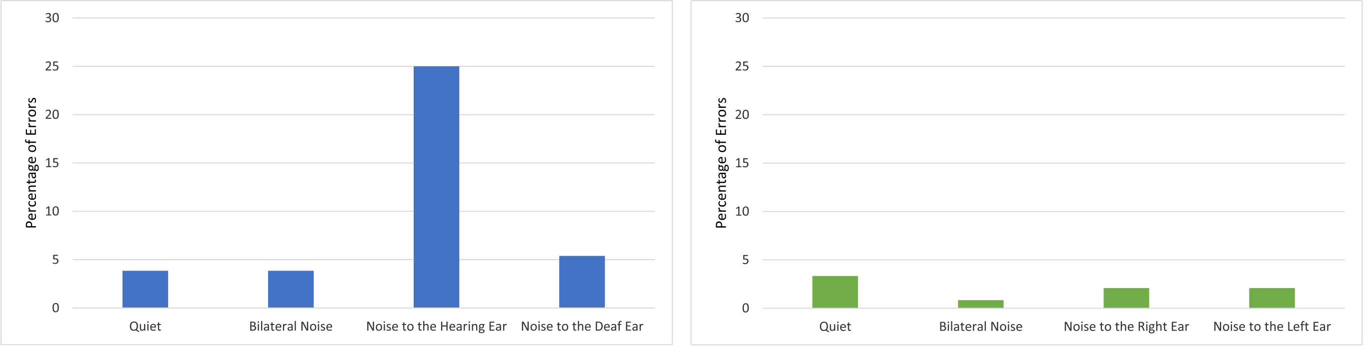


Fig. 1. Percentage of errors in the UHL (left) and NH (right) groups in response to the different experimental conditions. Friedman ANOVA test showed a difference among the conditions ($p < 0.001$) for the UHL group, where the Noise to the Hearing Ear condition produced the highest percentage of errors. This statistically significant difference was not found in the NH group ($p = 0.357$).

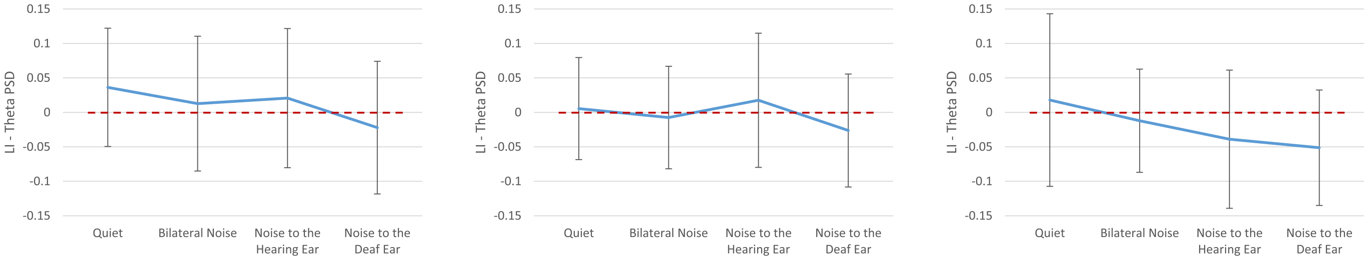


Fig. 2. Lateralization Index results in temporal and central areas in the UHL group. The graphs show the average lateralization index (LI) calculated in theta band for the UHL group in the different experimental conditions. Left graph shows results obtained for the T3-T4 electrodes pair, centre graph for the T5-T6 electrodes pair and right graph for the C3-C4 electrodes pair. The dotted line marks the zero value. Positive LI values stand for an asymmetry towards the Hearing Ear side cerebral activity, while negative LI values stand for an asymmetry towards the Deaf Ear side cerebral activity. Vertical bars denote standard deviations.

electrodes pair. While the results were just below statistical significance for the C3-C4 (Friedman ANOVA Chi Sqr. ($n = 13$, $df = 3$) $= 7.431$ $p = 0.059$) electrodes pair (Fig. 2 right).

Comparing the UHL and NH groups, for the F7-F8 electrodes pair, a statistically significant difference was shown among the lateralized noise conditions, which was when the noise was emitted from a source located +90° and −90° in relation to the participant (Kruskal-Wallis H (3, $n = 50$) $= 10.491$ $p = 0.015$). The NH group showed cortical activity always asymmetric to the Left Ear side, while the UHL group towards the side ipsilateral to the ear in the direction of the noise (Fig. 3).

In addition, for the F7-F8 electrodes pair, there was a difference between the groups also in the Bilateral noise condition, with the NH group lateralizing towards the Left Ear side and the UHL group towards the Hearing Ear side (Mann-Whitney *U* test $U = 25.000$ $Z = -2.883$ $p = 0.004$) (Fig. 4).

3.3. Alpha band

The UHL group showed a statistical significance for the T3-T4 electrodes pair in the comparison among the experimental conditions (ANOVA F (3,36) $= 3.409$ $p = 0.028$), in particular with a difference between Noise to the Hearing Ear and Noise to the Deaf Ear conditions ($p = 0.005$). In addition, when considering the lateralized noise conditions, the asymmetry was ipsilateral to the side of the noise direction (Fig. 5).

Furthermore, similarly to results obtained in theta band, comparing the F7-F8 electrodes pair LI in the UHL and NH groups in the lateralized noise conditions, there was a trend of asymmetry in the NH group towards the left side, independently of the direction of the noise, whilst in the UHL group the asymmetry was towards the side ipsilateral to the noise direction (Kruskal-Wallis H (3, $n = 50$) $= 7.036$ $p = 0.071$) (Fig. 6).

Moreover, for the F7-F8 electrodes pair, in the comparison between the UHL and NH groups in the Bilateral Noise condition, similarly to theta band activity, the NH group showed left-side asymmetry while the UHL group showed a higher activity on the Hearing Ear side (Mann-Whitney *U* test $U = 38.000$ $Z = 2.176$ $p = 0.029$) (Fig. 7).

Finally, in the NH group, for the C3-C4 electrodes pair, a significant effect of the factor experimental condition was found (Friedman ANOVA Chi Sqr. ($n = 12$, $df = 3$) $= 8.300$ $p = 0.040$), with the Quiet condition characterized by left-sided asymmetry while all the noise conditions were characterized by right-sided asymmetry (Fig. 8).

3.4. Beta band

In the NH group, for the C3-C4 electrodes pair, similarly to the alpha band activity, a statistical significance was found in the comparison among the conditions (ANOVA F (3, 33) $= 3.471$ $p = 0.027$). Specifically, the Quiet condition was the only one characterized by left-sided asymmetry, while the noise conditions were characterized by right-sided asymmetry (Fig. 9 left). In addition, there was a statistical difference between the Quiet and the Noise to the Left Ear condition ($p = 0.005$).

Also for the F7-F8 electrodes pair there was a statistical difference among the experimental conditions (ANOVA F (3, 33) $= 3.085$ $p = 0.040$), highlighting left-sided asymmetry in the Quiet conditions and right-sided asymmetry in the noise conditions (Fig. 9 right). In particular, the Quiet condition was statistically significantly different from all the experimental noise conditions (Bilateral Noise $p = 0.032$; Noise to the Right Ear $p = 0.045$; Noise to the Left Ear $p = 0.013$).

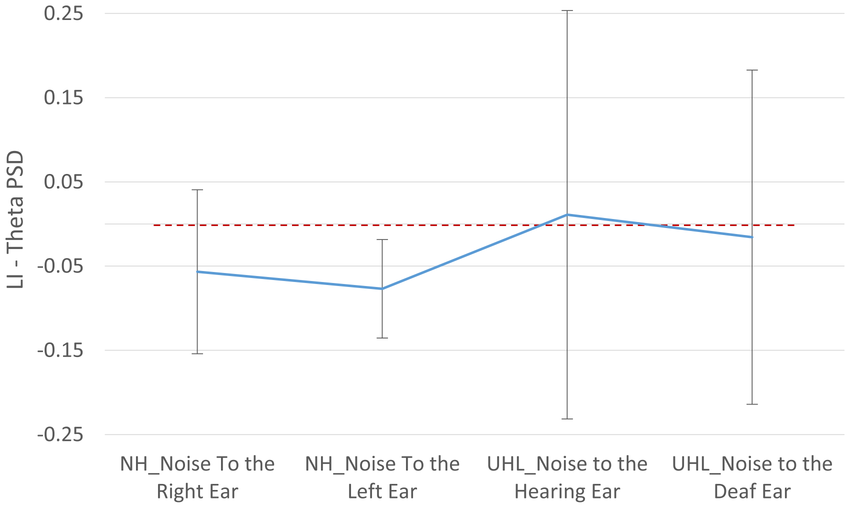


Fig. 3. Lateralization Index results in the frontal area in the NH and the UHL groups in correspondence of lateralized noise conditions. The graph shows the average lateralization index (LI) calculated in theta band for the F7-F8 electrodes pair for the UHL and NH groups in the different experimental conditions. The dotted line marks the zero value. Positive LI values for the UHL (NH) group stand for asymmetry towards the Hearing Ear side (Right) cerebral activity, while negative LI values stand for asymmetry towards the Deaf Ear side (Left) cerebral activity. Vertical bars denote standard deviations.

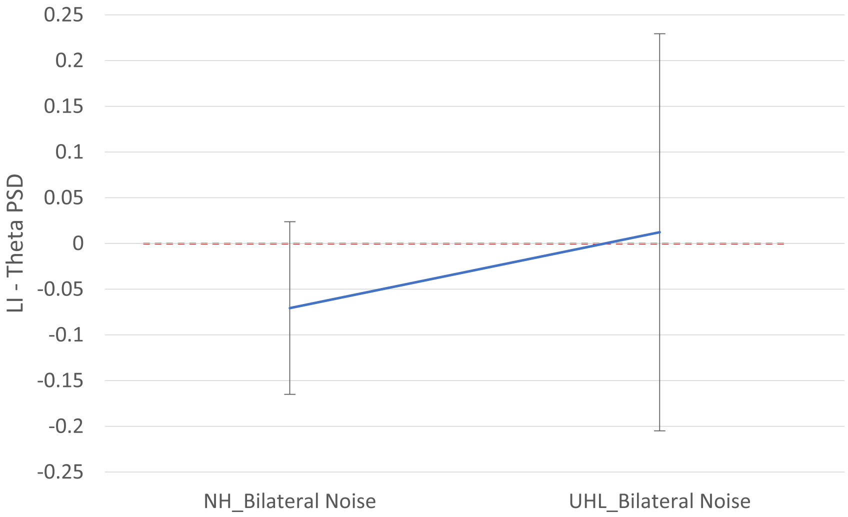


Fig. 4. Lateralization Index results in the frontal area in the NH and the UHL groups in correspondence of the Bilateral Noise condition. The graph shows the lateralization index (LI) calculated in theta band for the F7-F8 electrodes pair for the UHL and NH groups in the Bilateral noise condition. The dotted line marks the zero value. Positive LI values for the UHL (NH) group stand for asymmetry towards the Hearing Ear side (Right) cerebral activity, while negative LI values stand for asymmetry towards the Deaf Ear side (Left) cerebral activity. Vertical bars denote standard deviations.

3.5. *Gamma band*

In the NH group, in the comparison among the experimental conditions, for the F7-F8 electrodes pair a difference was revealed (ANOVA $F(3, 33) = 2.910$ $p = 0.049$), with the Quiet condition showing left-sided asymmetry, while the noise conditions were characterized by right-sided asymmetry (Fig. 10). In addition, the Quiet condition showed a statistical difference with the Bilateral Noise condition ($p = 0.013$) and a result just below the statistical significance with the Noise to the Left Ear condition ($p = 0.058$). Similar results were obtained also for the F7-F8 electrodes pair in beta band, and in the C3-C4 electrodes pair in beta and alpha bands.

3.6. *Correlation between LI and period of deafness*

Concerning the frontal area, specifically F3-F4 electrodes pair, it was found a positive correlation between the period of deafness (in years) and the LI values almost in all the EEG bands and in all the experimental conditions ($p < 0.05$; except for the Theta LI in the Quiet condition $p = 0.060$ and the Bilateral Noise condition $p = 0.052$, and for the Alpha LI in the Bilateral Noise condition $p = 0.075$). These results showed therefore a higher asymmetry in favour of the Hearing Ear side in correspondence of a longer period of deafness. On the contrary, in the temporal area it was not found any correlation between LI and period of deafness. Furthermore, in the parietal area, P3-P4 electrodes pair, there was a positive correlation between LI and period of deafness in all the investigated EEG bands, in the Quiet and Bilateral Noise condition ($p < 0.05$). Finally, in the occipital area, O1-O2 electrodes pair, there was a positive correlation between almost all the investigated EEG bands (except for Theta) and the period of deafness, in all the experimental conditions ($p < 0.05$).

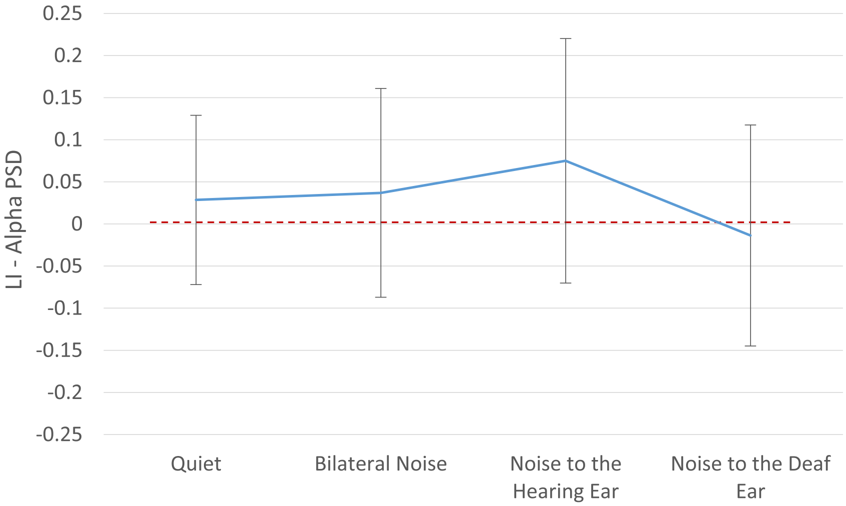


Fig. 5. Lateralization Index results in the temporal area in the UHL group. The graph shows the average lateralization index (LI) calculated in alpha band for the T3-T4 electrodes pair for the UHL group in the different experimental conditions. The dotted line marks the zero value. Positive LI values for the UHL group stand for asymmetry towards the Hearing Ear side cerebral activity, while negative LI values stand for asymmetry towards the Deaf Ear side cerebral activity. Vertical bars denote standard deviations.

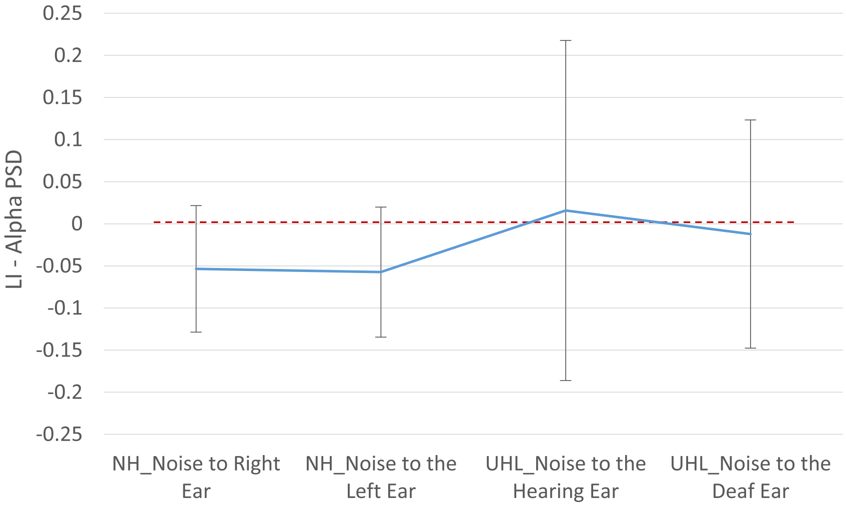


Fig. 6. Lateralization Index results in the frontal area in the NH and the UHL groups in correspondence of lateralized noise conditions. The graph shows the average lateralization index (LI) calculated in alpha band for the F7-F8 electrodes pair for the UHL and NH groups in the different experimental conditions. The dotted line marks the zero value. Positive LI values for the UHL (NH) group stand for asymmetry towards the Hearing Ear side (Right) cerebral activity, while negative LI values stand for asymmetry towards the Deaf Ear side (Left) cerebral activity. Vertical bars denote standard deviations.

4. Discussion

The left hemisphere specialization for linguistic functions under “normal” conditions is well-known, so that the auditory system therefore shows a dominant leftward lateralization for language processing (Tervaniemi and Hugdahl, 2003; Zatorre et al., 1992). In the present results concerning the NH sample, for beta and gamma bands in the inferior frontal region (F7-F8 electrodes pair) (Fig. 9 right and Fig. 10) and for alpha and beta bands in the central area (C3-C4 electrodes pair) (Figs. 8 and 9 left) this was reflected by the Quiet condition, but not by the conditions characterized by background noise. It is interesting to note that in the Quiet condition the left hemisphere was more involved, while in noise conditions the asymmetry was towards the right hemisphere, in agreement with previous studies on event related potentials, showing increased right hemisphere involvement during speech-in-noise processing, possibly reflecting the recruitment of additional brain resources to aid speech recognition (Bidelman and Dexter, 2015; Du et al., 2014; Shtyrov et al., 1999, 1998).

As a comment on this, the present data concerning theta and alpha rhythms in the NH group showed a consistent left lateralization in inferior frontal areas (F7-F8 channel) despite the presence of background noise (Figs. 3 and 6 respectively), in agreement with previous evidence showing a partial disengagement at poorer SNRs in the same areas but a lack of right lateralization with increasing noise (Bidelman and Howell, 2016). It is interesting to note that this left lateralization was independent of the noise direction, in contrast to the UHL group, in which the lateralization was: i) ipsilateral to the noise direction and ii) of a smaller amplitude in comparison to the leftward lateralization extent reported by the NH group. Given the coincidence between F7 electrode location and Brodmann's areas 44/45/47 (Koessler et al., 2009; Okamoto et al., 2004; Wakita, 2014), corresponding to the Broca area, whose language production and comprehension implications are dealt with

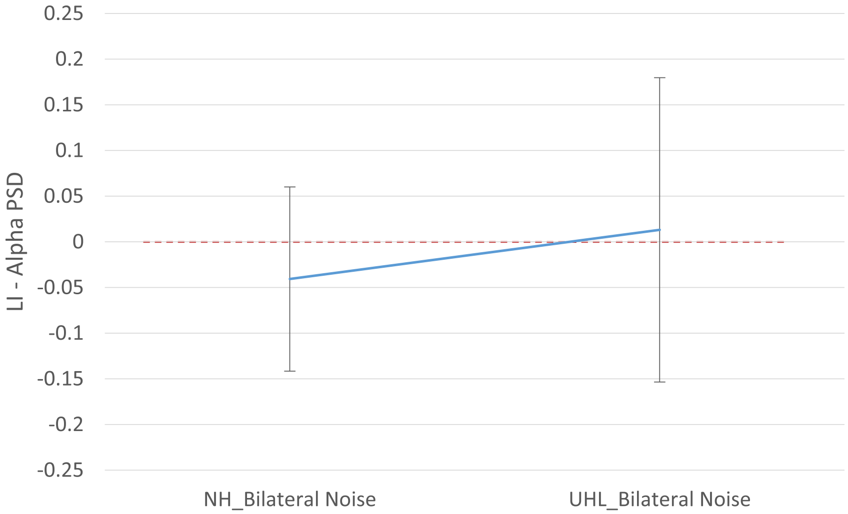


Fig. 7. Lateralization Index results in the frontal area in the NH and the UHL groups in correspondence of the Bilateral Noise condition. The graph shows the lateralization index (LI) calculated in alpha band for the F7-F8 electrodes pair for the UHL and NH groups in the Bilateral Noise condition. The dotted line marks the zero value. Positive LI values for the UHL (NH) group stand for asymmetry towards the Hearing Ear side (Right) cerebral activity, while negative LI values stand for asymmetry towards the Deaf Ear side (Left) cerebral activity. Vertical bars denote standard deviations.

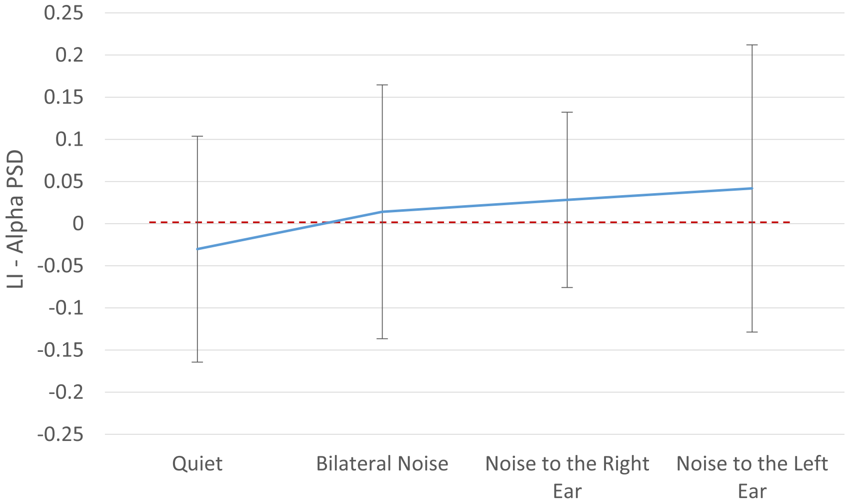


Fig. 8. Lateralization Index results in the central area in the NH group. The graph shows the average lateralization index (LI) calculated in alpha band for the C3-C4 electrodes pair for the NH group in the different experimental conditions. The dotted line marks the zero value. Positive LI values for the NH group stand for asymmetry towards the Right hemisphere's cerebral activity, while negative LI values stand for asymmetry towards the Left hemisphere's cerebral activity. Vertical bars denote standard deviations.

below, it appears extremely important that the activity in this anatomical site was always left-lateralized (as expected) in the NH group, whereas in the UHL group it elicited a differential site activity based on noise provenience, and a lateralization (as indexed by LI values) of a weaker extent.

This suggests two possible alternative interpretations: i) an incomplete lateralization specialization in the UHL group, as a result of an incomplete auditory development (Spironelli and Angrilli, 2010), or ii) a differential (widened) strategy for speech in noise recognition in the UHL group, in accordance with the theories of additional area involvement in the auditory network in order to deal with challenging auditory conditions (Fedorenko and Thompson-Schill, 2014). According to this, in a study examining evoked potentials before and after cochlear implant surgery in a single-side deaf (SSD) child, it was indeed proposed for such frontal activity a role in the compensation for cognitive load and effortful listening (Sharma et al., 2016). In addition, this evidence could be related to a different working memory involvement pattern, since in NH participants working memory tasks employing verbal stimuli elicited more consistent activation in the left Broca region than non-verbal tasks, which on the contrary more consistently activated dorsal and medial premotor areas (Rottschy et al., 2012). Furthermore, a study on NH participants, investigating the attention shift between two alternative signal sources, showed a greater power in the parietal areas of the hemisphere ipsilateral to the attentional cue, especially in mu, alpha, and beta bands (Thorpe et al., 2012). The possible implications of the verbal working memory and of the attention in the context of facing challenging listening conditions, in the present case represented by masked auditory information due to the presence of background noise and/or hearing impairments, have also been suggested in a very recent review by Peelle (2018), hypothesising the occurrence of multiple dissociable processes for the understanding of degraded speech. Moreover, among the above mentioned processes, decision-making

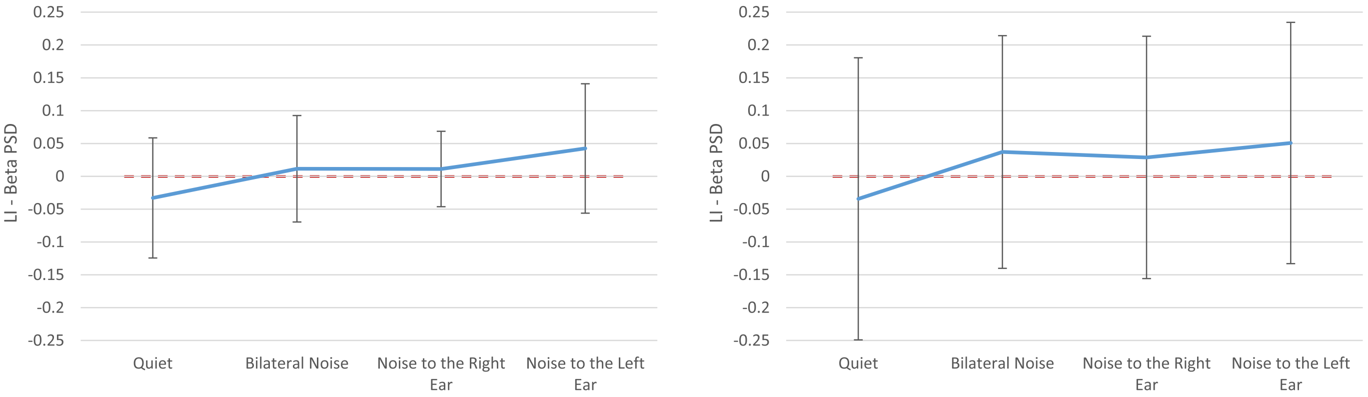


Fig. 9. Lateralization Index results in the central and frontal areas in the NH group. The graphs show the average lateralization index (LI) calculated in beta band for the NH group in the different experimental conditions. Left graph shows results obtained for the C3-C4 electrodes pair and right graph for the F7-F8 electrodes pair. The dotted line marks the zero value. Positive LI values for the NH group stand for asymmetry towards the Right hemisphere's cerebral activity, while negative LI values stand for asymmetry towards the Left hemisphere's cerebral activity. Vertical bars denote standard deviations.

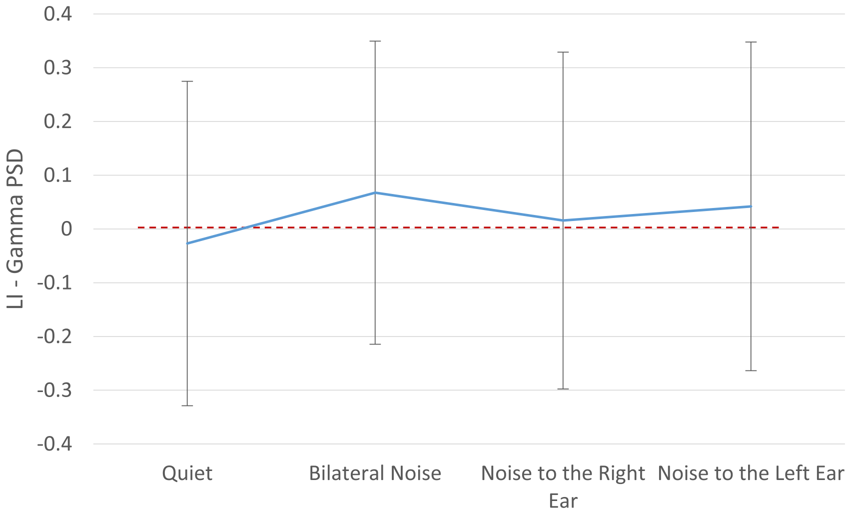


Fig. 10. Lateralization Index results in the frontal area in the NH group. The graph shows the average lateralization index (LI) calculated in gamma band for the F7-F8 electrodes pair for the NH group in the different experimental conditions. The dotted line marks the zero value. Positive LI values for the NH group stand for asymmetry towards the Right hemisphere's cerebral activity, while negative LI values stand for asymmetry towards the Left hemisphere's cerebral activity. Vertical bars denote standard deviations.

is also involved since recent evidence suggests a role in the process for the auditory cortex, in addition to frontal and parietal areas (King et al., 2018). Furthermore, a segregation of specialization has been found, due to the correlation between the activity in the parietal cortices with the accuracy of sound identification and the activity in the inferior frontal lobe and decision-making processes, during auditory perception tasks (Binder et al., 2004). In the light of these two just mentioned evidences, it is interesting to note that present results concerning the correlation between the period of deafness (in years) and the LI values suggested higher asymmetry toward the Hearing Ear side in correspondence of a longer period of deafness. This evidence in the frontal area (F3-F4 electrodes pair) could be related to decision making process more lateralized to the Hearing Ear side, while in the parietal (P4-P4 electrodes pair) and occipital area (O1-O2 electrodes pair) it could be linked to multi-modal integration (Jiwani et al., 2016), as well more lateralized to the Hearing Ear side.

Concerning beta LI results, showing a higher left lateralization in Quiet conditions in the NH group, this can be linked to findings showing a greater high beta amplitude in the left in comparison to the right anterior regions during phonological and semantic tasks (Spironelli and Angrilli, 2010). On the other hand, the present highlighted right lateralization in beta power during noise conditions would seem to be due to the noise background inducing a possible wider network than the typical left lateralized one.

Together, results in beta and gamma bands in the NH participants, showing leftward asymmetry in inferior frontal areas (F7-F8 electrodes pair) in the Quiet condition, but rightward lateralization in the noise conditions, could be linked to recent results proposing that beta (high-beta) and gamma bands could be specific brain oscillations involved in speech-in-noise recognition (Cabrera et al., 2018). The present results, however, suggest a wider specific activity involving central areas (C3-C4) in alpha and beta bands.

Concerning the difference found among the different experimental conditions in alpha and theta bands mainly in the temporal (Fig. 2 left and centre and Fig. 5) and in the central areas (Fig. 2 right), it is worth noting that it was detected only in the UHL group but not in the NH group. As expected, NH participants did not exhibit a lateralization of the activity in the temporal area as supported by several results showing a bilateral activation when intelligible speech stimuli were processed (Crinion et al., 2003; Davis and Johnsrude, 2003; Evans et al., 2016; Hassanpour et al., 2015; McGettigan et al., 2012; Westerhausen et al., 2014). This suggests that, in the NH group, although the asymmetry between left and right temporal areas occurred during speech processing (Specht, 2014), the asymmetry extent is smaller than in UHL participants, showing in fact a statistically significant difference in the LI values among the experimental conditions. Furthermore, the asymmetry in UHL appeared to be different among the conditions, with the asymmetry towards the Deaf Ear side almost only in the case of the Noise directed towards the Deaf Ear (Fig. 2 left and centre and Fig. 5) (therefore ipsilaterally to the noise, similarly to what was already observed in the inferior frontal areas – F7-F8 electrode pair - in theta and alpha bands). This would suggest that in most conditions the principally activated temporal area in UHL is the same as the Hearing Ear side, but when the noise was directed towards the opposite side, the contralateral temporal area would be mainly activated.

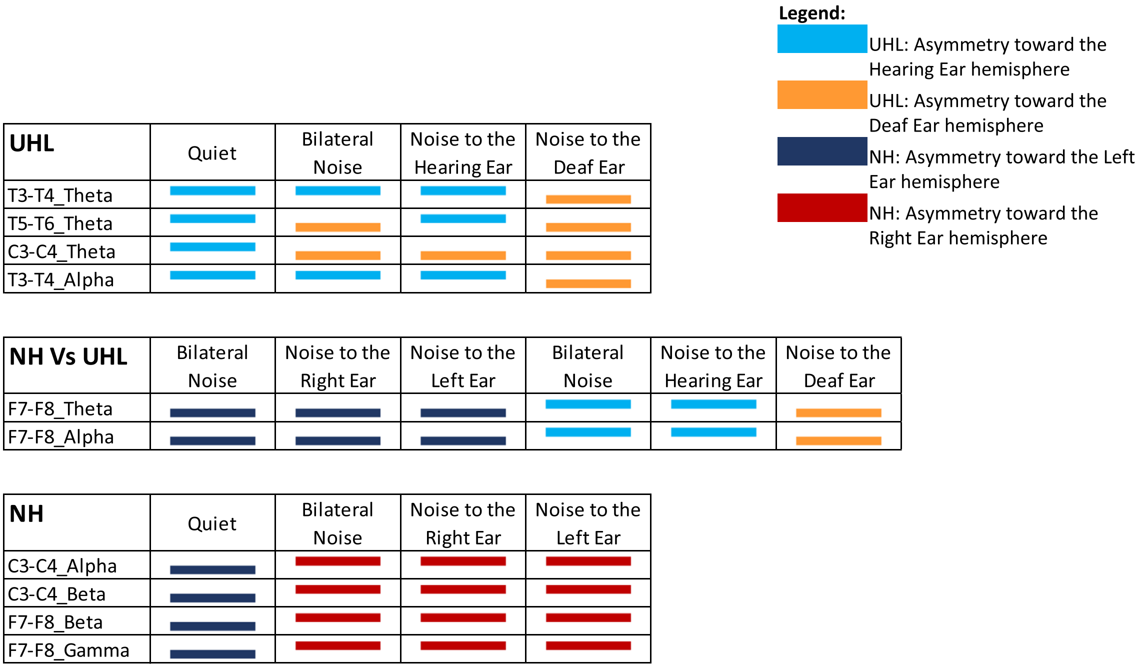
The sum of the results (for a summary of the present results, please see Table 2) makes it possible to address the questions raised in the introduction section:

1. the UHL group showed a different activation pattern in comparison to NH children, both in frontal and temporal areas. In particular, this suggests a strategy consisting of the principal/by default asymmetry pattern located in the cerebral hemisphere of the Hearing Ear Side, but subjected to changes on the basis of the presence of irrelevant stimuli (background noise) directed towards the contralateral Deaf Ear, producing a shift of the cerebral activity asymmetry towards the hemisphere ipsilateral to the noise direction
2. as expected, on the basis of the percentage of errors reported for each of the experimental conditions, the most difficult one for UHL children proved to be the one with the noise directed towards the hearing ear and frontal signal; this was apparently not reflected by particular asymmetry patterns, since no correlations were found between the performances demonstrated by patients in the lateralized noise (directed towards the Hearing Ear or the Deaf Ear side) experimental conditions and asymmetry data

5. Conclusions

To the best of our knowledge the present study is the first to identify a particular lateralization pattern in UHL children, lateralizing on the basis of the direction of the background noise. In fact, in contrast to the left-lateralization shown by NH children independently of background noise direction, the UHL children's cerebral activity asymmetry was ipsilateral to noise direction and of a weaker extent than in NH controls. Furthermore, in the case of an overlap between the direction of the signal and the noise (Bilateral Noise condition), although NH children maintained the left lateralization, the UHL group's asymmetry was in favour of the Better Ear side's inferior frontal regions. The sum of these main results confirms the involvement of additional auditory regions besides the temporal ones in the case of challenging auditory conditions, and extends this concept to the lateralization's modulation in UHL children on the basis of the background noise direction. In fact, in temporal areas the UHL group showed a consistent Hearing Side hemisphere asymmetry, except for the condition in which the noise was directed towards the Deaf Ear Side. Concerning EEG rhythms, alpha and theta bands seem to represent the more characteristic and sensitive neurophysiological features in the temporal areas in UHL, whereas considering the NH group the particular neurophysiological features appear to be gamma and beta in the inferior frontal areas, and alpha and beta in the central areas. Finally, in the comparison between UHL and NH groups the most characterising

Table 2
Summary of LI results shown in the present study. Evidence of asymmetry patterns as expressed by the lateralization index (LI) is reported in the table. The first column reports the electrode pairs on which the LI was calculated. UHL: unilateral hearing loss children; NH: normal hearing children. The UHL group showed most of the activity located in the Hearing Ear hemisphere, and NH children in the Left Ear hemisphere. These tendencies were modulated by the presence of background noise in the case of NH children in central and frontal areas, and by the direction of the noise in UHL children, shifting the asymmetry ipsilaterally to the noise direction in temporal and frontal areas.



Legend:
🟦 UHL: Asymmetry toward the Hearing Ear hemisphere
🟧 UHL: Asymmetry toward the Deaf Ear hemisphere
⬛ NH: Asymmetry toward the Left Ear hemisphere
🟥 NH: Asymmetry toward the Right Ear hemisphere

UHL	Quiet	Bilateral Noise	Noise to the Hearing Ear	Noise to the Deaf Ear
T3-T4_Theta	🟦	🟦	🟦	🟧
T5-T6_Theta	🟦	🟧	🟦	🟧
C3-C4_Theta	🟦	🟧	🟧	🟧
T3-T4_Alpha	🟦	🟦	🟦	🟧

NH Vs UHL	Bilateral Noise	Noise to the Right Ear	Noise to the Left Ear	Bilateral Noise	Noise to the Hearing Ear	Noise to the Deaf Ear
F7-F8_Theta	⬛	⬛	⬛	🟦	🟦	🟧
F7-F8_Alpha	⬛	⬛	⬛	🟦	🟦	🟧

NH	Quiet	Bilateral Noise	Noise to the Right Ear	Noise to the Left Ear
C3-C4_Alpha	⬛	🟥	🟥	🟥
C3-C4_Beta	⬛	🟥	🟥	🟥
F7-F8_Beta	⬛	🟥	🟥	🟥
F7-F8_Gamma	⬛	🟥	🟥	🟥

features seem to be theta and alpha bands in inferior frontal areas.

Our findings may help introduce an objective measure of hearing deprivation-induced cortical plasticity changes and listening effort in the assessment of children with SSD. In turn, this could contribute to establishing more appropriate candidacy criteria for the treatment of this population by means of cochlear implantation.

From a larger perspective, the EEG lateralization index is a promising objective outcome measure of binaural hearing restoration in subjects with monoaural hearing, such as those with UHL receiving a hearing aid or a cochlear implant, or those with bilateral deafness using a unilateral cochlear implant and undergoing sequential cochlear implantation.

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