applied sciences

MDPI

Article

Neural Mechanisms Related to the Enhanced Auditory Selective Attention Following Neurofeedback Training: Focusing on Cortical Oscillations

Hwan Shim [1,*], Leah Gibbs [2], Karsyn Rush [2], Jusung Ham [2], Subong Kim [3], Sungyoung Kim [1,4] and Inyong Choi [2,5]

[1] Department of Electrical and Computer Engineering Technology, Rochester Institute of Technology, Rochester, NY 14623, USA; sungyoung.kim@kaist.ac.kr
[2] Department of Communication Sciences and Disorders, University of Iowa, Iowa City, IA 52242, USA; leah-gibbs@uiowa.edu (L.G.); karsyn-rush@uiowa.edu (K.R.); jusung-ham@uiowa.edu (J.H.); inyong-choi@uiowa.edu (I.C.)
[3] Department of Communication Sciences and Disorders, Montclair State University, Montclair, NJ 07043, USA; kimsub@montclair.edu
[4] Graduate School of Culture Technology, Korea Advanced Institute of Science and Technology, Daejeon 34141, Republic of Korea
[5] Graduate School of Convergence Science and Technology, Seoul National University, Seoul 08826, Republic of Korea
* Correspondence: hxsiee@rit.edu

Abstract: Selective attention can be a useful tactic for speech-in-noise (SiN) interpretation as it strengthens cortical responses to attended sensory inputs while suppressing others. This cortical process is referred to as attentional modulation. Our earlier study showed that a neurofeedback training paradigm was effective for improving the attentional modulation of cortical auditory evoked responses. However, it was unclear how such neurofeedback training improved attentional modulation. This paper attempts to unveil what neural mechanisms underlie strengthened auditory selective attention during the neurofeedback training paradigm. Our EEG time–frequency analysis found that, when spatial auditory attention was focused, a fronto-parietal brain network was activated. Additionally, the neurofeedback training increased beta oscillation, which may imply top-down processing was used to anticipate the sound to be attended selectively with prior information. When the subjects were attending to the sound from the right, they exhibited more alpha oscillation in the right parietal cortex during the final session compared to the first, indicating improved spatial inhibitory processing to suppress sounds from the left. After the four-week training period, the temporal cortex exhibited improved attentional modulation of beta oscillation. This suggests strengthened neural activity to predict the target. Moreover, there was an improvement in the strength of attentional modulation on cortical evoked responses to sounds. The Placebo Group, who experienced similar attention training with the exception that feedback was based simply on behavioral accuracy, did not experience these training effects. These findings demonstrate how neurofeedback training effectively improves the neural mechanisms underlying auditory selective attention.

Keywords: selective attention; auditory modulation; neural oscillation

check for updates

Citation: Shim, H.; Gibbs, L.; Rush, K.; Ham, J.; Kim, S.; Kim, S.; Choi, I. Neural Mechanisms Related to the Enhanced Auditory Selective Attention Following Neurofeedback Training: Focusing on Cortical Oscillations. *Appl. Sci.* **2023**, *13*, 8499. https://doi.org/10.3390/app13148499

Academic Editor: Douglas O'Shaughnessy

Received: 16 May 2023
Revised: 7 July 2023
Accepted: 17 July 2023
Published: 23 July 2023

Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Actively managing conversations in social interactions, known as "speech in noise (SiN)" understanding, recruits selective attention: enhancement of target speech and inhibition of noise. Large variance in understanding SiN is observed, even for individuals with normal hearing [1,2]. Poor understanding of SiN may be related to a decline in selective attention, due to the role of selective attention in enhancing target speech and inhibiting noise [3]. According to our recent finding [4], attentional modulation on neural encoding of acoustic inputs in the auditory cortex (AC) would be a crucial neural mechanism for

successful SiN understanding. This finding showed that the amplitude ratio of auditory cortical responses to the target speech and noise during a SiN task correlated with behavioral SiN performance [5–8].

Recent studies [9,10] demonstrated that training on maintaining attention to low-intensity signals extracted from background noise improved SiN performance and was transferable to untrained stimuli. In these studies, both auditory segregation and selective attention were involved in the training effects. To explicitly reinforce attentional modulation of cortical auditory evoked responses, our previous study created a neurofeedback training paradigm [11]. Two voice streams—spoken by a high-pitched and a low-pitched speaker—were played from different directions (left and right) with no physical overlap in time (i.e., no energetic masking) to maximize stream segregation. Subjects were tasked with focusing on one voice stream at a time. Throughout this auditory selective attention training, 64-channel electroencephalography (EEG) decoded auditory selective attention from single-trial EEG signals [12–14]. Only the Experimental Group participants received visual feedback based on the EEG-based attention decoder. The Control Group went through a comparable selective attention training program without receiving neurofeedback to rule out a placebo effect. The accuracy of attention decoding from single-trial EEG signals reflects the strength of attentional modulation on cortical auditory evoked responses [13]. Therefore, giving users the outcome of EEG-based attention decoding in the form of neurofeedback [15] may strengthen their attentional modulation of cortical response.

However, it is still elusive which neural mechanisms enable strengthened auditory selective attention and which crucial auditory cues drive the training effect in the neurofeedback training paradigm, where the competing streams varied in location, speaker identity, and tempo to maximize stream segregation. This poses the question of how to reveal what neural mechanisms and auditory cues explicitly reinforce attentional modulation of cortical auditory evoked responses. The present study utilized the induced oscillation activity to investigate this. More specifically, this paper provides further analyses of our previous data [11] focusing on how cortical oscillations changed over the course of repeated training.

A fronto-parietal brain network is activated when spatial auditory attention is focused. Attention to spatial auditory features leads to increased fronto-parietal network activity in functional magnetic resonance imaging (fMRI; [16–20]), electroencephalography (EEG; [21]), and magnetoencephalography (MEG; [22]). Similar to visual spatial attention, auditory spatial attention causes parietal lateralization of alpha oscillation power in the intraparietal sulcus (IPS; [21,23–25]). Alpha lateralization varies systematically when attentional focus changes, similar to vision [26]. Alpha lateralization is more transient if non-spatial characteristics encourage stream segregation, but it is persistent when competing streams are comparable aside from spatial attributes [23].

Spatial signals are nevertheless an efficient means for focusing top-down attention while having a weak role in auditory grouping and streaming [27–29]. Both bottom-up auditory cues and top-down cognitive processes are used when listening to speech in noisy environments [30]. There are low-level oscillatory cortical mechanisms that use sensory sampling or prediction while maintaining different neural rhythms based on the task [31]. As previous work supports, the beta wave employs top-down processing to transmit descending information [32]. The brain relies extensively on predictions and expectations to fill in the blanks, thus employing prior information.

Therefore, we hypothesize that while a subject actively recruits selective attention during the task, the alpha band oscillation would be present in the IPS, and the beta band oscillation would be located in the middle temporal gyrus (MTG), superior temporal sulcus (STS), and inferior frontal gyrus (IFG) during the preparatory period. The preparatory period represents the time interval between the presentation of the auditory cue and the target speech with the masker, during which a cognitive process to steer the listeners' selective attention is expected to emerge.

2. Materials and Methods

This study utilized data from [11]. As such, most methods are consistent with the previous study.

2.1. Participants

A total of 20 native American English speakers with normal hearing thresholds were recruited from the University of Iowa student population (mean age: 23.2 years, SD: 1.33 years, 6 males: 30%). All the participants had 20 dB HL or lower thresholds at any tested frequency, measured in octaves from 250 to 8000 Hz. After consenting to participate in the trial, participants were randomized to either the Experimental or Placebo Group (i.e., single-blinded design). All participants underwent four consecutive weeks of training lasting one hour per week, as well as pre- and post-training speech-in-noise (SiN) tests at their first and last visits. The work was finished in compliance with the International Medical Association's Code of Ethics, and written informed consent was acquired (Declaration of Helsinki). The Institutional Review Board at the University of Iowa examined and approved all study methods [11].

A power analysis based on the effect size reported by earlier perceptual training studies, such as [9], can support the sample size. These estimates indicated that 10 people per group would be needed for the current study, assuming a significance level of 0.05 and a power of 0.80. We chose a 4-week training period, as did [9], in order to (1) ensure overnight consolidation, which has been claimed to be essential for perceptual training [33–35] and (2) prevent learning and memory of speech stimuli that were used in pre- and post-training tests [36,37].

2.2. Task Design and Procedures

2.2.1. Attention Training Procedure: Experimental Group

Three overlapping auditory streams were presented during each training session: a male voice saying the word "down" four times from the right (+30 azimuth) loudspeaker, a female voice saying the word "up" five times from the left (−30 azimuth), and an unrelated distractor noise that sounds like a water splash played three times intermittently from the loudspeaker directly in front of the subject. The presentation level was 70 dB SPL calibrated using an SPL meter which means the experiment's auditory stimulus was played at a volume that led the SPL meter to indicate 70 dB in the listening position, and this level was verified each time the experiment was performed. A visual cue ("Target: Up" or "Target: Down") was used for each of the 120 trials during each visit to direct participants' attention to the "up" or "down" stream (60 trials each). The attended stream was decoded from the EEG after the stimuli were shown. After each trial, visual feedback ("+" sign on the screen going up or down) was presented to show the decoded direction of attention (i.e., whether the "up" or "down" stream" was attended). An example of a trial going "down" stream is shown in Figure 1 [11].

2.2.2. Attention Training Procedure: Placebo Group

The Placebo Group heard the similar three overlapping auditory streams with the exception that one of the last three (for the "up" stream) or two (for the "down" stream) utterances in each stream had a three-semitone higher pitch. These streams consisted of isochronous repetitions of "up" and "down" spoken by the female and male speakers with a distractor noise. They chose the utterance with a higher pitch in the attended stream by hitting the number key as the visual cue directed their attention to either the "up" or "down" stream in each trial (i.e., an oddball detection task within a trial). Depending on the correctness of their button response, they received visible feedback ("Correct" or "Incorrect") after pressing the button [11].

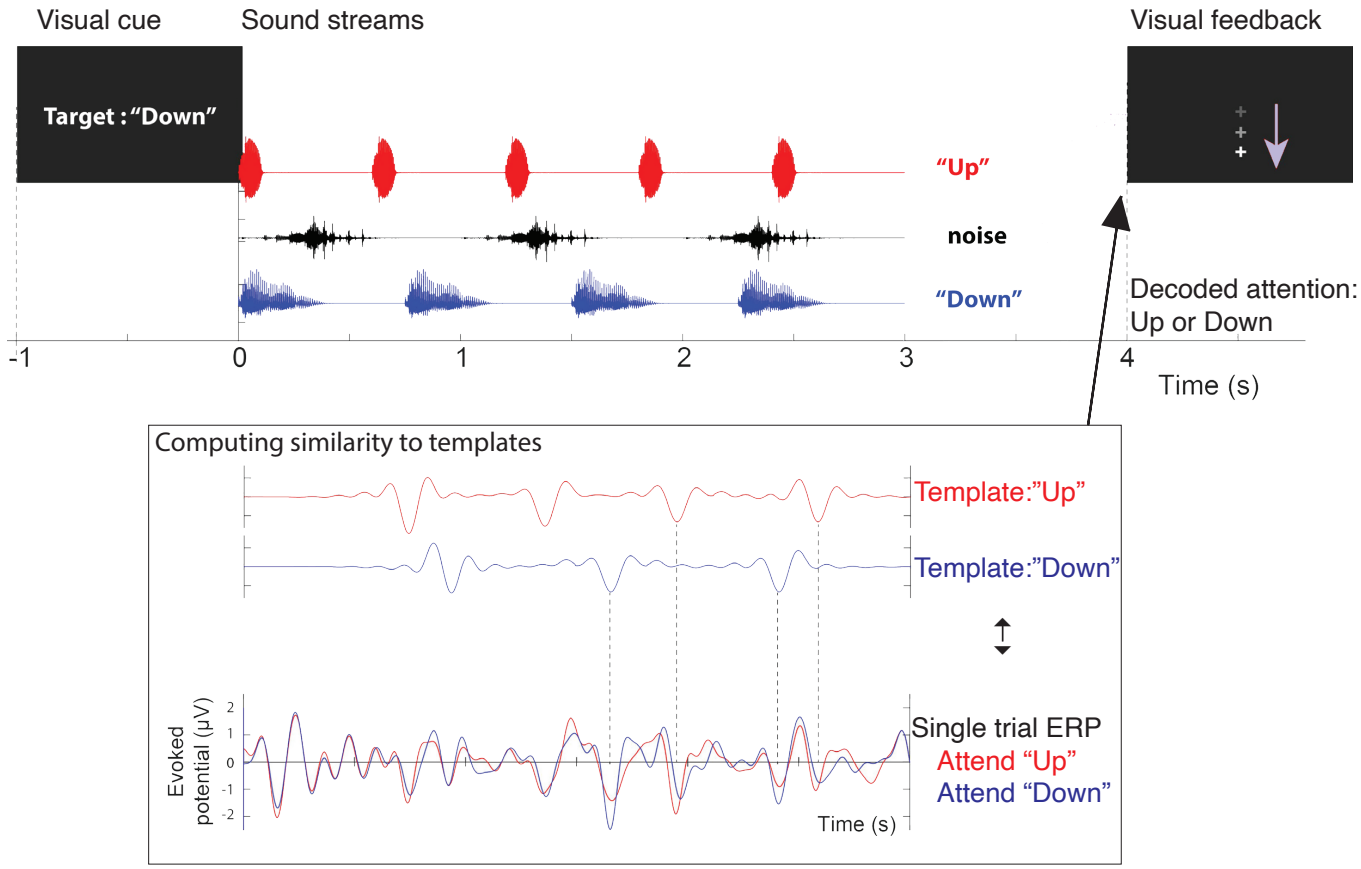


Figure 1. An example of the neurofeedback training's trial structure assigned to the Experimental Group. An attend-*down* case is shown [11].

2.3. Induced Oscillatory Activity Analysis

Using the BioSemi ActiveTwo system, 64 channels of scalp EEG data were captured throughout the training tasks at a sampling rate of 2048 Hz using the international 10–20 configuration. For the induced oscillatory activity analysis, 64-channel EEG data from 5 subjects in the Experimental Group and 10 subjects in the Placebo Group were collected and analyzed. EEG data from the other 5 subjects in the Experimental could not be used since the full 64-channel single-trial data were not saved for later off-line analyses in the version used for those subjects, while the behavioral and single-trial EEG classification analysis could be applied to all the 20 subjects.

A template-matching approach was utilized to decode the attended stream from single-trial EEG signals and deliver neurofeedback to the Experimental Group [13]. EEG recordings from linked mastoids were averaged and re-referenced to the front-central channels (Fz, FCz, FC1, FC2, and Cz). After baseline correction and bandpass filtering between 1 and 9 Hz, EEG data were compared to two template waveforms created from grand-average cortical evoked responses to the single "up" and "down" streams while passive listening in silence. The attention was decoded by choosing the template that has a larger correlation coefficient with the single-trial EEG data. The fixation cross was then moved upward or downward on the computer screen to provide visual feedback in response to the detection of attention on the "up" stream or "down" stream, respectively.

The spectrograms were processed from the resampled EEG signal per channel and trial based on a 256-sample fast Fourier transform with a period of 64 samples and an overlap of 63 samples in 256 Hz sampling rate. These spectrograms were categorized into "up" or "down", and weeks. The paired t-tests between "up" and "down" every week were taken. Furthermore, the paired t-test between "up"−"down" in week 4 and "up"−"down"

in week 1 were taken to explore the difference in the attentional modulation. In addition, the cluster-based permutation analysis was performed to find the significantly different clusters of attentional modulation between week 4 and week 1 for the Experimental Group and the Placebo Group [38]. To observe the difference between week 4 and week 1 in each alpha and beta oscillation, we selected frequency bands for each alpha and beta range (8–13 Hz and 24–29 Hz, respectively), set the minimum cluster length as around 50 ms, and set the p-values for the t-test as 0.05 in the spectrograms. For the Experimental Group and the Placebo Group, the cluster-based permutation analysis was performed separately in each alpha and beta band and the obtained clusters implied the statistically significant difference between week 4 and week 1 for each group.

Source localization is needed to analyze temporal dynamics with the estimated source spatial distribution because sensor data in some channels may not sufficiently capture the geographic distribution of neural sources and the temporal dynamics of ERP components [39]. The inverse operator was estimated using minimum norm estimation (MNE) [40–42] based on assumptions of multiple sparse priors [43] on an average template brain in order to project the sensor space data into source space. By using the inverse operator, source space time courses of ERPs were acquired over all cortical voxels in both hemispheres. As a method of noise normalization, they were projected onto the cortical maps to create dynamic statistical parametric maps (dSPMs) [44]. Each cluster for beta and alpha waves in the preparatory period was selected and all voxels were averaged during each selected cluster for beta and alpha waves. The timely averaged voxels were presented as snapshots of the clusters for the Experimental Group and the Placebo Group.

3. Results

3.1. Enhanced Attentional Modulation

A single-trial EEG waveform and the grand-average cortical evoked responses to the single "up" and "down" streams were compared using Pearson correlation coefficients to decode selective attention. With continued training, attentional modulation altered over time. In the Experimental Group, the mean decoding accuracy increased monotonically from 55.9% (SD = 4.1%) in the first week to 57.4% (SD = 6.2%) in the second week, 58.0% (SD = 3.8%) in the third week, and 60.2% (SD = 3.7%) in the fourth week. The Placebo Group, on the other hand, did not exhibit a progression in attentional modulation with time. For the first, second, third, and most recent weeks, the mean decoding accuracies were 60.7, 59.7, 54.1, and 58.9%, respectively. The relative standard deviations were 7.0, 3.5, 5.0, and 3.4% [11].

A two-way mixed ANOVA on the decoding accuracy observed in the first and last week was conducted to further investigate the effect of training time (first vs. fourth week), the type of feedback (neurofeedback vs. behavioral), and the interaction of those effects on the attentional modulation (i.e., quantified as the decoding accuracy). There were no significant main effects of time ($F_{1,18}$ = 0.99, p = 0.33) or group ($F_{1,18}$ = 1.0, p = 0.32) on decoding accuracy, indicating that (1) there was no baseline difference in attentional modulation between the groups and (2) there was no significant improvement in attentional modulation over time with repeated training. However, the results showed a significant interaction between time and group ($F_{1,18}$ = 5.7, p = 0.028), showing that the effects of training on attentional modulation over time varied significantly between the groups. In the Experimental Group, the post hoc paired t-test between decoding accuracy in the first and last weeks showed a Bonferroni corrected p-value of 0.022 (six times the uncorrected p-value of 0.0036) [11].

3.2. Induced Cortical Activity Changes in Source Space Topography to Selective Attention

Examining the ERPs acquired at the sensor space was the initial step in determining the EEG data's quality. The induced cortical activity from the EEG data was able to be assessed due to the clear auditory components (like N1) discovered from the front-central channels.

T-tests were taken between "Up" and "Down" in the spectrogram domain for week 1 and week 4, and of "Up"−"Down" in the spectrogram between week 4 and week 1 to analyze the difference of auditory modulation for both the Experimental Group and the Placebo Group. The cluster-based permutation tests were performed in the spectrogram which included the difference of attentional modulation between week 4 and week 1. Significantly different clusters were obtained within alpha and beta wave ranges (8–13 Hz and 24–29 Hz, respectively), in the Experimental Group, displayed as solid-line boxes in Figure 2A. These significant differences were not observed in the Placebo Group, so in order to indicate the regions of interest, the clusters from the Experimental Group were displayed as dotted line boxes in Figure 3A. As the clusters showed, attentional modulation was significantly improved only in the Experimental Group which received neurofeedback in every trial. When examining the alpha and beta waves in the preparatory timeline (from −1 to 0 s), each cluster appeared in the alpha and beta frequency ranges. The sensor space topographies and the source space topographies for both groups were averaged in the time–frequency range of the clusters from the Experimental Group, shown in Figure 2B,C and Figure 3B,C. The sensor space topographies of the beta oscillation within the cluster show a significantly stronger power on the parietal region of both hemispheres in week 4 of the Experimental Group. The source space topographies of the beta wave range indicate more power on MTG, STS, and IFG of both hemispheres in week 4 of the Experimental Group, illustrated in Figure 2B. The beta oscillations expand their role to anticipate selective attention on the given auditory cues during preparatory time periods in week 4 of the Experimental Group. Between week 1 and week 4 of the Placebo Group, there was no significant difference in the sensor space and source space topographies of the beta wave range during the preparatory time periods.

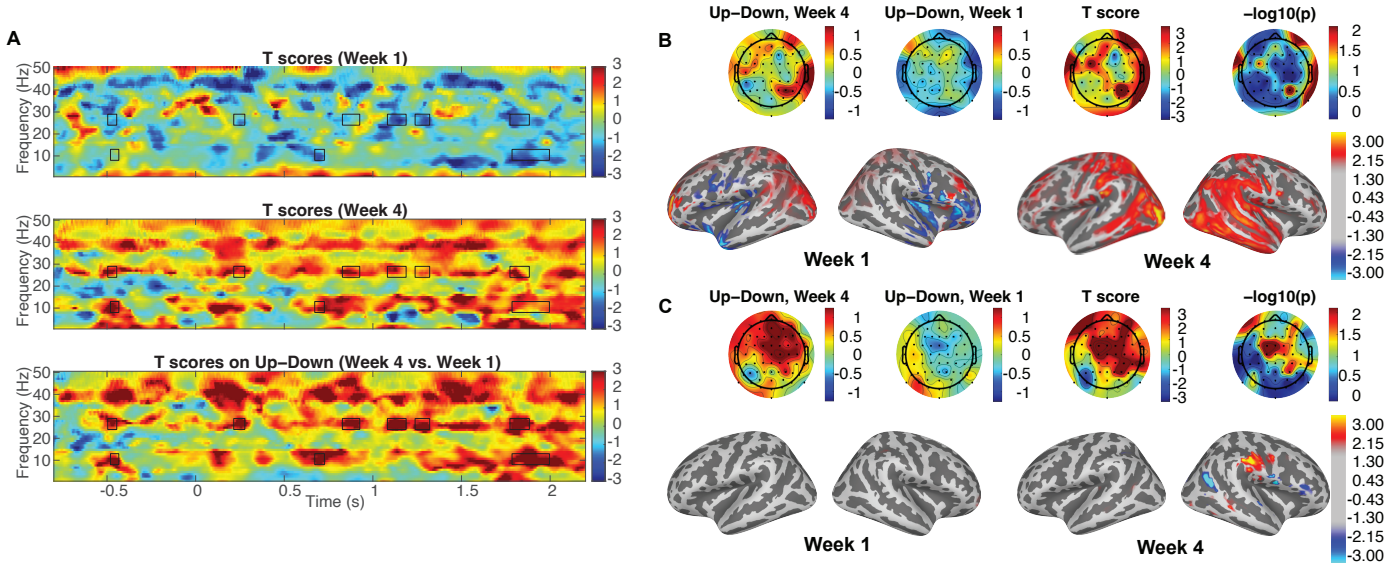


Figure 2. Spectrograms and topographies of induced activities in the Experimental Group. (**A**) The t-score spectrograms of auditory modulation between "Up" and "Down" in week 1, week 4 and the t-score spectrogram of "Up" vs. "Down" between week 4 and week 1 are obtained during the neurofeedback training from the Experimental Group. The solid-line boxes indicate significantly different clusters within the alpha and beta wave ranges (8–13 Hz and 24–29 Hz, respectively), obtained by the cluster-based permutation tests from the Experimental Group [38]. (**B**) The topographies of the beta wave cluster are obtained in the preparatory time range before target speech onset (from −0.50 to −0.45 s) at the sensor space and source space. (**C**) The topographies of the alpha wave cluster are obtained in the preparatory time range before target speech onset (from −0.48 to −0.43 s) at the sensor space and source space.

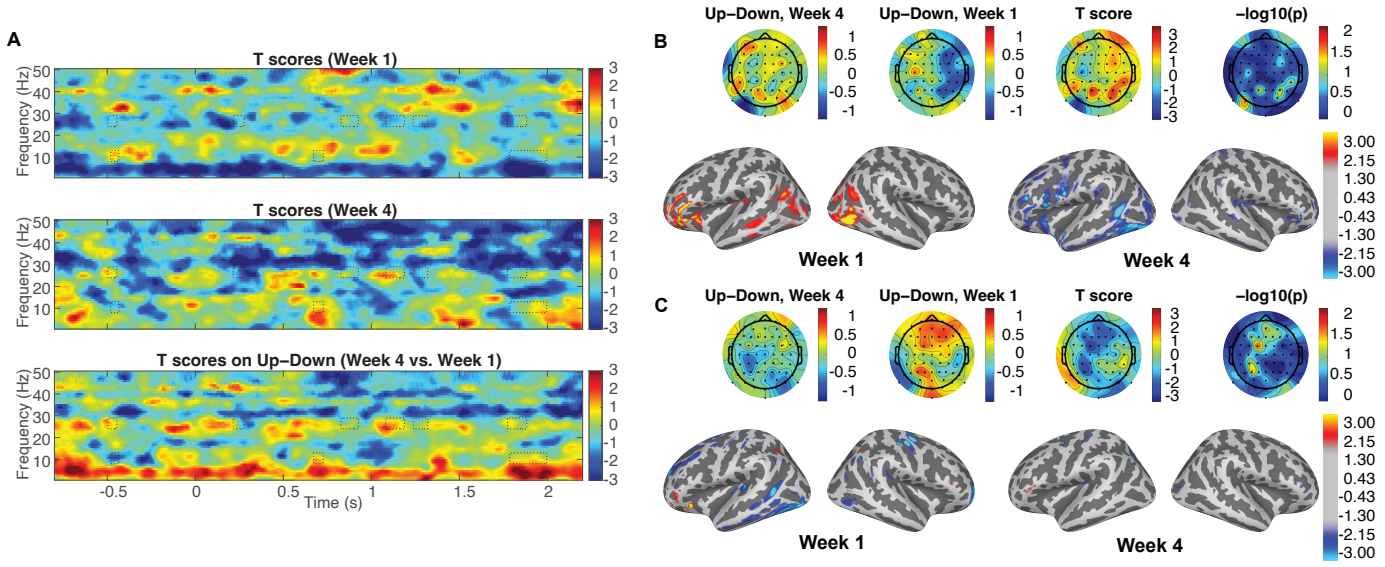


Figure 3. Spectrograms and topographies of induced activities in the Placebo Group. (**A**) The t-score spectrograms of auditory modulation between "Up" and "Down" in week 1, week 4, and between week 4 and week 1 are obtained during the neurofeedback training from the Placebo Group. No significantly different clusters are found in the Placebo Group. To indicate where the regions of interest are, the dotted line boxes indicate significantly different clusters within the alpha and beta wave ranges (8–13 Hz and 24–29 Hz, respectively), obtained by the cluster-based permutation tests from the Experimental Group [38]. (**B**) The mean topographies of the beta wave cluster taken from the Placebo Group are obtained in the preparatory time range before target speech onset (from −0.50 to −0.45 s) at the sensor space and source space. (**C**) The topographies of the alpha wave cluster taken from the Placebo Group are obtained in the preparatory time range before target speech onset (from −0.48 to −0.43 s) at the sensor space and source space.

The sensor space topographies of the alpha wave range from the time periods of the cluster show a significantly strong power on the right parietal region in week 4 of the Experimental Group. The source space topographies of the alpha wave range show more power on IPS of the right hemisphere in week 4 of the Experimental Group in Figure 2C. The alpha oscillations increase to inhibit the left auditory stimuli during preparatory time periods in week 4 of the Experimental Group. During the preparatory time periods, there was no significant difference in the sensor space and source space topographies of the alpha wave range between week 1 and week 4 of the Placebo Group.

4. Discussion

4.1. Conclusions

The current study investigated what cortical mechanisms are involved when auditory selective attention is improved by perceptual training. For this purpose, we further analyzed our previous dataset [11] which demonstrated the efficacy of our neurofeedback training paradigm for improving auditory selective attention [4–11]. By examining induced cortical oscillations, in the Experimental Group (who received neurofeedback), we found that alpha (~10 Hz) and beta (~25 Hz) oscillations in the right parietal cortex increase over the course of training. The Placebo Group (who did not receive neurofeedback) did not show any significant change in cortical oscillations. There was no significant change in alpha and beta oscillations in the Placebo Group. These findings provide novel perspectives of the brain plasticity related to enhanced auditory selective attention following neurofeedback training, which was not provided by our previous report [11]. We claim that the stronger beta oscillation in the Experimental Group indicates more strongly engaged top-down processing to predict forth-coming sounds to attend in advance [45,46]. Beta oscillation is believed to be related to top-down prediction based on the context of

stimuli [46,47]. Especially, enhancement in beta is observed during the tasks that require top-down attention [48,49]. Theves et al. [50] showed that for the audiovisual onset synchrony task, the preparatory beta oscillations in the central, parietal, and temporal lobes increased after training. Our result indicates that this is also true in more auditory-centered tasks. Our result provides more support with contrasting outcomes in the Placebo Group where no neurofeedback was given.

Likewise, the increase in alpha oscillation in the right parietal region can be interpreted as enhanced inhibitory processing to ignore competing sounds. According to Viswanathan et al. [51], single-trial speech intelligibility in speech-in-noise tasks considerably correlates with, and independently contributes to the overall magnitudes of alpha power in parieto-occipital EEG channels and beta power in frontal channels. Furthermore, Price et al. [52] demonstrated that accuracy in SiN is predicted by the alpha modulation between clean and noise-degraded speech. Similarly, in this study, SiN results were improved when alpha power modulation was shown across the training period in the Experimental Group, and SiN results were not improved when alpha power modulation was not shown across the training in the Placebo Group [11]. Moreover, as in Obleser and Weisz [53], the enhancement of alpha in the parietal region can be used as a predictor of the SiN results. The right parietal stimulation of alpha was observed, but rightward spatial attention was not enhanced, consistent with the results by Deng et al. [54]. It is also consistent with the finding by Frey et al. [55] that the parietal cortex is asymmetrical and alpha oscillation inhibits contralateral attention. In addition, as in the topography of Deng et al. [26], parieto-occipital alpha power during the attentional preparatory period appeared strongly on the right side despite attention to the left side. Additionally, the topographies were asymmetric and did not show a linear relationship with attention along the side from left to right. This could be because the left auditory cortex mainly localizes stimuli in the contralateral space, while the right auditory cortex processes stimuli in the whole space [55].

4.2. Limitations of the Study

There are several limitations of this study. First, the current experimental paradigm divided the Experimental Group and the Placebo Group depending on whether visual neurofeedback was given or not. A future study will also be conducted on how attentional modulation would change when neurofeedback is intentionally provided to participants as incorrect results by randomizing visual feedback.

The concurrent speech streams were disparate in location, speaker identity, and tempo in order to maximize stream separation. Both parietal alpha oscillation and temporal beta oscillation were observed during the preparatory period when the subjects were focused, and valid feedback was provided. This indicates both spatial and pitch-related mechanisms contributed. In order to specify key auditory cues that contribute to the training effect, future research should test the effectiveness of various auditory cues for selective attention training and determine whether these cues are also present in a more general SiN task.

Pearson correlation coefficients between the grand-average cortical evoked responses and a single-trial EEG waveform were used for decoding selective attention in this study. The intraclass correlation coefficients might be used for the decoder. For the follow-up study, it would be considered if the decoding algorithm is updated to improve the mean decoding accuracy by using machine learning algorithms. Also, the whole 64-channel EEG data from a smaller number of subjects in the Experimental Group were used for the induced activity analysis, and the small sample size in one group was a limitation of this study. A future study will recruit a greater number of subjects.

This study did not reveal whether the training impact endures after the training time or disappears. A follow-up study is anticipated to investigate this question. Lastly, because selective listening in background noise is hampered by peripheral hearing loss [56], additional research is required to examine the training effect in clinical populations (e.g., hearing aid or cochlear implant users [11]).

Author Contributions: Conceptualization, I.C.; methodology, I.C. and H.S.; software, I.C. and H.S.; validation, H.S., J.H., L.G., K.R. and S.K. (Sungyoung Kim); formal analysis, I.C. and H.S.; investigation, S.K. (Subong Kim); resources, I.C.; data curation, L.G. and K.R.; writing—original draft preparation, H.S.; writing—review and editing, H.S., L.G., J.H. and I.C.; visualization, H.S.; supervision, I.C.; project administration, I.C.; funding acquisition, I.C. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the American Otological Society Research Grant and the Department of Defense Hearing Restoration Research Program Grant (W81XWH-19-1-0637) awarded to I.C., as well as NIDCD P50 (DC000242 31).

Institutional Review Board Statement: The work was finished in compliance with the International Medical Association's Code of Ethics, and we acquired written informed consent (Declaration of Helsinki). The Institutional Review Board at the University of Iowa examined and approved all study methods.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Kumar, G.; Amen, F.; Roy, D. Normal Hearing Tests: Is a Further Appointment Really Necessary? *J. R. Soc. Med.* **2007**, *100*, 66. [CrossRef]
2. Moore, D.R.; Rosen, S.; Bamiou, D.E.; Campbell, N.G.; Sirimanna, T.; James Bellis, T.; Chermak, G.; Weihing, J.; Musiek, F.; Dillon, H.; et al. Evolving Concepts of Developmental Auditory Processing Disorder (APD): A British Society of Audiology APD Special Interest Group "White Paper". *Int. J. Audiol.* **2013**, *52*, 3–13. [CrossRef]
3. Bressler, S.; Goldberg, H.; Shinn-Cunningham, B. Sensory Coding and Cognitive Processing of Sound in Veterans with Blast Exposure. *Hear. Res.* **2017**, *349*, 98. [CrossRef]
4. Kim, S.; Schwalje, A.T.; Liu, A.S.; Gander, P.E.; McMurray, B.; Griffiths, T.D.; Choi, I. Pre- and Post-Target Cortical Processes Predict Speech-in-Noise Performance. *Neuroimage* **2021**, *228*, 117699. [CrossRef]
5. Hillyard, S.A.; Hink, R.F.; Schwent, V.L.; Picton, T.W. Electrical Signs of Selective Attention in the Human Brain. *Science* **1973**, *182*, 177–180. [CrossRef] [PubMed]
6. Hillyard, S.A.; Vogel, E.K.; Luck, S.J. Sensory Gain Control (Amplification) as a Mechanism of Selective Attention: Electrophysiological and Neuroimaging Evidence. *Philos. Trans. R. Soc. B Biol. Sci.* **1998**, *353*, 1257. [CrossRef] [PubMed]
7. Mesgarani, N.; Chang, E.F. Selective Cortical Representation of Attended Speaker in Multi-Talker Speech Perception. *Nature* **2012**, *485*, 233–236. [CrossRef] [PubMed]
8. Carcea, I.; Insanally, M.N.; Froemke, R.C. Dynamics of Auditory Cortical Activity during Behavioural Engagement and Auditory Perception. *Nat. Commun.* **2017**, *8*, 14412. [CrossRef] [PubMed]
9. Whitton, J.P.; Hancock, K.E.; Polley, D.B. Immersive Audiomotor Game Play Enhances Neural and Perceptual Salience of Weak Signals in Noise. *Proc. Natl. Acad. Sci. USA* **2014**, *111*, E2606–E2615. [CrossRef]
10. Whitton, J.P.; Hancock, K.E.; Shannon, J.M.; Polley, D.B. Audiomotor Perceptual Training Enhances Speech Intelligibility in Background Noise. *Curr. Biol.* **2017**, *27*, 3237–3247.e6. [CrossRef]
11. Kim, S.; Emory, C.; Choi, I. Neurofeedback Training of Auditory Selective Attention Enhances Speech-In-Noise Perception. *Front. Hum. Neurosci.* **2021**, *15*. [CrossRef] [PubMed]
12. Kerlin, J.R.; Shahin, A.J.; Miller, L.M. Attentional Gain Control of Ongoing Cortical Speech Representations in a "Cocktail Party". *J. Neurosci.* **2010**, *30*, 620–628. [CrossRef] [PubMed]
13. Choi, I.; Rajaram, S.; Varghese, L.A.; Shinn-Cunningham, B.G. Quantifying Attentional Modulation of Auditory-Evoked Cortical Responses from Single-Trial Electroencephalography. *Front. Hum. Neurosci.* **2013**, *7*, 115. [CrossRef] [PubMed]
14. O'Sullivan, J.A.; Power, A.J.; Mesgarani, N.; Rajaram, S.; Foxe, J.J.; Shinn-Cunningham, B.G.; Slaney, M.; Shamma, S.A.; Lalor, E.C. Attentional Selection in a Cocktail Party Environment Can Be Decoded from Single-Trial EEG. *Cereb. Cortex* **2015**, *25*, 1697–1706. [CrossRef]
15. Sherlin, L.H.; Arns, M.; Lubar, J.; Heinrich, H.; Kerson, C.; Strehl, U.; Sterman, M.B. Neurofeedback and Basic Learning Theory: Implications for Research and Practice. *J. Neurother.* **2011**, *15*, 292–304. [CrossRef]
16. Alho, K.; Salmi, J.; Koistinen, S.; Salonen, O.; Rinne, T. Top-down Controlled and Bottom-up Triggered Orienting of Auditory Attention to Pitch Activate Overlapping Brain Networks. *Brain Res.* **2015**, *1626*, 136–145. [CrossRef]

17. Hill, K.T.; Miller, L.M. Auditory Attentional Control and Selection during Cocktail Party Listening. *Cereb. Cortex* **2010**, *20*, 583–590. [CrossRef] [PubMed]
18. Kong, L.; Michalka, S.W.; Rosen, M.L.; Sheremata, S.L.; Swisher, J.D.; Shinn-Cunningham, B.G.; Somers, D.C. Auditory Spatial Attention Representations in the Human Cerebral Cortex. *Cereb. Cortex* **2014**, *24*, 773–784. [CrossRef] [PubMed]
19. Michalka, S.W.; Kong, L.; Rosen, M.L.; Shinn-Cunningham, B.G.; Somers, D.C. Short-Term Memory for Space and Time Flexibly Recruit Complementary Sensory-Biased Frontal Lobe Attention Networks. *Neuron* **2015**, *87*, 882–892. [CrossRef]
20. Noyce, A.L.; Cestero, N.; Michalka, S.W.; Shinn-Cunningham, B.G.; Somers, D.C. Sensory-Biased and Multiple-Demand Processing in Human Lateral Frontal Cortex. *J. Neurosci.* **2017**, *37*, 8755–8766. [CrossRef]
21. Banerjee, S.; Snyder, A.C.; Molholm, S.; Foxe, J.J. Oscillatory Alpha-Band Mechanisms and the Deployment of Spatial Attention to Anticipated Auditory and Visual Target Locations: Supramodal or Sensory-Specific Control Mechanisms? *J. Neurosci.* **2011**, *31*, 9923–9932. [CrossRef]
22. Huang, S.; Chang, W.-T.; Belliveau, J.W.; Hämäläinen, M.; Ahveninen, J. Lateralized Parietotemporal Oscillatory Phase Synchronization during Auditory Selective Attention. *Neuroimage* **2014**, *86*, 461–469. [CrossRef]
23. Bonacci, L.M.; Bressler, S.; Shinn-Cunningham, B.G. Nonspatial Features Reduce the Reliance on Sustained Spatial Auditory Attention. *Ear Hear.* **2020**, *41*, 1635–1647. [CrossRef]
24. Bonacci, L.M.; Dai, L.; Shinn-Cunningham, B.G. Weak Neural Signatures of Spatial Selective Auditory Attention in Hearing-Impaired Listeners. *J. Acoust. Soc. Am.* **2019**, *146*, 2577. [CrossRef]
25. Tune, S.; Wöstmann, M.; Obleser, J. Probing the Limits of Alpha Power Lateralisation as a Neural Marker of Selective Attention in Middle-Aged and Older Listeners. *Eur. J. Neurosci.* **2018**, *48*, 2537–2550. [CrossRef]
26. Deng, Y.; Choi, I.; Shinn-Cunningham, B. Topographic Specificity of Alpha Power during Auditory Spatial Attention. *Neuroimage* **2020**, *207*, 116360. [CrossRef]
27. Darwin, C.J.; Hukin, R.W. Auditory Objects of Attention: The Role of Interaural Time Differences. *J. Exp. Psychol. Hum. Percept. Perform.* **1999**, *25*, 617–629. [CrossRef]
28. Sach, A.J.; Bailey, P.J. Some Characteristics of Auditory Spatial Attention Revealed Using Rhythmic Masking Release. *Percept. Psychophys.* **2004**, *66*, 1379–1387. [CrossRef]
29. Shinn-Cunningham, B.G. Object-Based Auditory and Visual Attention. *Trends Cogn. Sci.* **2008**, *12*, 182–186. [CrossRef]
30. Strait, D.L.; Kraus, N. Can You Hear Me Now? Musical Training Shapes Functional Brain Networks for Selective Auditory Attention and Hearing Speech in Noise. *Front. Psychol.* **2011**, *2*, 113. [CrossRef]
31. Arnal, L.H.; Giraud, A.L. Cortical Oscillations and Sensory Predictions. *Trends Cogn. Sci.* **2012**, *16*, 390–398. [CrossRef]
32. Wang, X.J. Neurophysiological and Computational Principles of Cortical Rhythms in Cognition. *Physiol. Rev.* **2010**, *90*, 1195–1268. [CrossRef]
33. Fenn, K.M.; Nusbaum, H.C.; Margoliash, D. Consolidation during Sleep of Perceptual Learning of Spoken Language. *Nature* **2003**, *425*, 614–616. [CrossRef]
34. Eisner, F.; McQueen, J.M. Perceptual Learning in Speech: Stability over Time. *J. Acoust. Soc. Am.* **2006**, *119*, 1950. [CrossRef]
35. Davis, M.H.; Di Betta, A.M.; Macdonald, M.J.E.; Gaskell, M.G. Learning and Consolidation of Novel Spoken Words. *J. Cogn. Neurosci.* **2009**, *21*, 803–820. [CrossRef]
36. Bentler, R.A. List Equivalency and Test-Retest Reliability of the Speech in Noise Test. *Am. J. Audiol.* **2000**, *9*, 84–100. [CrossRef]
37. Booshardt, S.; Degonda, N.; Schmidt, C.F.; Boesiger, P.; Nitsch, R.M.; Hock, C.; Henke, K. One Month of Human Memory Consolidation Enhances Retrieval-Related Hippocampal Activity. *Hippocampus* **2005**, *15*, 1026–1040. [CrossRef]
38. Maris, E.; Oostenveld, R. Nonparametric Statistical Testing of EEG- and MEG-Data. *J. Neurosci. Methods* **2007**, *164*, 177–190. [CrossRef]
39. Tian, X.; Huber, D.E. Measures of Spatial Similarity and Response Magnitude in MEG and Scalp EEG. *Brain Topogr.* **2008**, *20*, 131–141. [CrossRef]
40. Hämäläinen, M.S.; Sarvas, J. Realistic Conductivity Geometry Model of the Human Head for Interpretation of Neuromagnetic Data. *IEEE Trans. Biomed. Eng.* **1989**, *36*, 165–171. [CrossRef]
41. Gramfort, A.; Luessi, M.; Larson, E.; Engemann, D.A.; Strohmeier, D.; Brodbeck, C.; Parkkonen, L.; Hämäläinen, M.S. MNE Software for Processing MEG and EEG Data. *Neuroimage* **2014**, *86*, 446–460. [CrossRef]
42. Gramfort, A.; Luessi, M.; Larson, E.; Engemann, D.A.; Strohmeier, D.; Brodbeck, C.; Goj, R.; Jas, M.; Brooks, T.; Parkkonen, L.; et al. MEG and EEG Data Analysis with MNE-Python. *Front. Neurosci.* **2013**, *7*, 267. [CrossRef]
43. Friston, K.; Harrison, L.; Daunizeau, J.; Kiebel, S.; Phillips, C.; Trujillo-Barreto, N.; Henson, R.; Flandin, G.; Mattout, J. Multiple Sparse Priors for the M/EEG Inverse Problem. *Neuroimage* **2008**, *39*, 1104–1120. [CrossRef]
44. Dale, A.M.; Liu, A.K.; Fischl, B.R.; Buckner, R.L.; Belliveau, J.W.; Lewine, J.D.; Halgren, E. Dynamic Statistical Parametric Mapping: Combining FMRI and MEG for High-Resolution Imaging of Cortical Activity. *Neuron* **2000**, *26*, 55–67. [CrossRef]
45. Engel, A.K.; Fries, P.; Singer, W. Dynamic Predictions: Oscillations and Synchrony in Top-down Processing. *Nat. Rev. Neurosci.* **2001**, *2*, 704–716. [CrossRef]
46. Bressler, S.L.; Richter, C.G. Interareal Oscillatory Synchronization in Top-down Neocortical Processing. *Curr. Opin. Neurobiol.* **2015**, *31*, 62–66. [CrossRef]
47. Engel, A.K.; Fries, P. Beta-Band Oscillations—Signalling the Status Quo? *Curr. Opin. Neurobiol.* **2010**, *20*, 156–165. [CrossRef]

48. Riddle, J.; Hwang, K.; Cellier, D.; Dhanani, S.; D'esposito, M. Causal Evidence for the Role of Neuronal Oscillations in Top–Down and Bottom–Up Attention. *J. Cogn. Neurosci.* **2019**, *31*, 768–779. [CrossRef]
49. Yuan, Z.; Chen, H.; Ding, Z.; Li, Z.; Song, Y.; Li, X. The Modulating Effect of Top-down Attention on the Optimal Pre-Target Onset Oscillatory States of Bottom-up Attention. *Neuroscience* **2021**, *466*, 186–195. [CrossRef]
50. Theves, S.; Chan, J.S.; Naumer, M.J.; Kaiser, J. Improving Audio-Visual Temporal Perception through Training Enhances Beta-Band Activity. *Neuroimage* **2020**, *206*, 116312. [CrossRef]
51. Viswanathan, V.; Bharadwaj, H.M.; Heinz, M.G.; Shinn-Cunningham, B.G. Induced Alpha And Beta Electroencephalographic Rhythms Covary With Single-Trial Speech Intelligibility In Competition. *Sci. Rep.* **2023**, *13*, 10216. [CrossRef]
52. Price, C.N.; Alain, C.; Bidelman, G.M. Auditory-Frontal Channeling in α and β Bands Is Altered by Age-Related Hearing Loss and Relates to Speech Perception in Noise. *Neuroscience* **2019**, *423*, 18–28. [CrossRef]
53. Obleser, J.; Weisz, N. Suppressed Alpha Oscillations Predict Intelligibility of Speech and Its Acoustic Details. *Cereb. Cortex* **2012**, *22*, 2466–2477. [CrossRef]
54. Deng, Y.; Reinhart, R.M.G.; Choi, I.; Shinn-Cunningham, B. Causal Links between Parietal Alpha Activity and Spatial Auditory Attention. *Elife* **2019**, *8*, e51184. [CrossRef]
55. Frey, J.N.; Mainy, N.; Lachaux, J.P.; Muller, N.; Bertrand, O.; Weisz, N. Selective Modulation of Auditory Cortical Alpha Activity in an Audiovisual Spatial Attention Task. *J. Neurosci.* **2014**, *34*, 6634–6639. [CrossRef]
56. Shinn-Cunningham, B.G.; Best, V. Selective Attention in Normal and Impaired Hearing. *Trends Amplif.* **2008**, *12*, 283–299. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.