



Original Article

Comparison of Regularity Detection between Individuals with and without Speech-in-Noise Problems using Electrophysiological Methods

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OBJECTIVE: To analyze the cortical representations of auditory regularities and the relation between these representations and speech-in-noise (SIN) abilities and to compare two groups of participants with different SIN abilities on these cortical measures.

MATERIALS and METHODS: In total, 22 participants aged 20–40 years with normal hearing and without noise exposure, brain stem level-processing issues, neurological/psychiatric issues, or related medication were presented with three different stimuli resembling auditory regularities appearing after random sounds as well as a random series of sounds. Participants received a total of 480 stimuli in passive and active phases each (in which they actively detected regularities). Evoked responses were recorded via 20-channel standard electroencephalography (EEG) cap.

RESULTS: The groups were not significantly different in terms of evoked potential parameters. A significant negative correlation was observed between amplitudes of responses evoked by decreasing the frequency regularity in the active phase and SIN scores. Response parameters were significantly different between the stimuli. Active phase latencies were shorter and amplitudes were higher than passive phase ones, except for two stimuli.

CONCLUSION: Cortical representations of decreasing frequency regularity are promising for revealing the link between SIN and representations of regularity detection. This paradigm is suggested to be applicable to individuals with clinical-level SIN problems [hearing aid (HA) and cochlear implant (CI) users, normal-hearing individuals, children with learning problems, children with dyslexia, and others] to reveal which process of SIN mechanism is defective; this is a complicated process with many sub-mechanisms. These results may be utilized in designing CI and HA algorithms (for more robust representations of auditory regularities) and rehabilitation programs.

KEYWORDS: Auditory regularity, speech-in-noise, electrophysiology

INTRODUCTION

Sounds in the auditory environment reach ears sequentially and simultaneously as mixtures. Listeners are often subjected to complex acoustic scenes formed by sounds emitted by different sound sources, as in a crowded shopping center or an orchestral concert. The allocation of these sound mixtures to sources is a complex process, including separation and analysis of signals that may belong to auditory objects, formation of schemas, and generalization between senses (voice to face match for a person)^[1,2]. The grouping of sound mixtures on the basis of their common characteristics and the formation of auditory objects are mechanisms of auditory scene analysis, postulated by Bregman^[3], where sounds are grouped on the basis of the similarity of spectral and temporal characteristics, later to be formed into mental representations.

In daily life, attending to a single speaker amidst noise involves these mechanisms. Timbre and loudness changes as well as spatial and temporal cues of sounds contribute to auditory grouping. The detection of these target sounds depends on the separation of auditory regularities from sound mixtures, e.g., detecting the sound of a ringing phone in a crowded office or the horn of a car in traffic. Speech-in-noise (SIN) is related to detecting auditory regularities, a process that has been investigated via cortical responses^[4]. For example, a repeating sound at a random frequency and a repeating three-sound pattern appearing after random frequency sounds have been found to be evoking magnetic 100 (M100) responses [electroencephalography (EEG) N1 response] in the root mean square amplitude waveform of magnetoencephalography recordings^[5,6]. In fact, cortical implications of auditory processes, ranging from the detection of sound onset to the detection of frequency changes as well as the detection of embedded gaps in continuous noise, are reflected on N1 responses, the magnetic counterpart of which is the M100 response^[7-12].

It is wise to assume that an issue faced by individuals with SIN difficulties may be deficient auditory regularity detection, keeping in mind its relationship with SIN. One way to investigate SIN by electrophysiological means is recording auditory late latency responses.

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es evoked by speech sounds in noise, showing response amplitude changes in comparison with silence^[13]. These changes were different in children with learning disabilities and in controls as well as in children with low SIN scores and in those with high SIN scores^[14,15].

In addition to repeating sound at a random frequency and repeating three-sound patterns, sound patterns decreasing and increasing in frequency may be recognized as auditory regularities as they represent fundamental frequency (Fo) trajectories in speech; tracking this is a mechanism for extracting the target message in the presence of masking sounds^[16]. These regularities have the potential to evoke specific cortical responses that have been observed in a series of studies by Chait et al.^[5,6,17]. Besides, cortical responses evoked by regularity detection may have different amplitude and latency characteristics between individuals with varying SIN abilities because of the relation between auditory regularity detection and SIN performance.

The present study includes the following hypotheses:

1. Time locked auditory N1 response will be evoked by the onset of a sound sequence formed by a repeating sound with a single frequency (reg) and by a series of sounds with regularly decreasing (dec) and increasing (ris) frequencies, appearing after a sequence of sounds with random frequencies.
2. No N1 response will be evoked by a sound sequence that is formed only by sounds with random frequencies.
3. The amplitudes and latencies of N1 will be different in groups of participants with high and low SIN performance.
4. There will be a negative correlation between SIN performance and N1 amplitude and latency.

MATERIALS and METHODS

The study sample included 22 participants aged 20–40 years without neurological–psychiatric disorders or psychiatric medication, musical training or practice (except for mainstream music classes), history of middle ear disorders, excessive noise exposure, and reported hearing loss. All participants had hearing thresholds equal to or better than 20 decibel (dB) Hearing Level (HL) (Jerger and Jerger, 1980; cited from Hall and Mueller^[18]) and speech discrimination scores in quiet equal to or better than 92%. Acoustic reflexes in at least two frequencies between 500–4000 Hertz (Hz) were obtained, and the reflex decay test at 500 Hz–1000 Hz was negative. All participants had a masking level difference (MLD) of 10.92 ± 2.32 dB to rule out any brainstem-level neural processing problem, and normal results were obtained in the Mini Mental Test^[19,20]. Approval from the University Ethical Committee of Non-Invasive Clinical Research was obtained on 4.9.2014, with registration number GO 14/406-09. All participants provided written informed consent.

The stimuli utilized in evoked potential testing were adapted from Chait et al.^[17]. In total, 20 equally log-spaced sounds between 222–2000 Hz (5 millisecond [ms] attack decay times, 30 ms total length) were created with Praat Software^[21]. Twenty-eight random sounds were randomly selected and sequenced from this pool of 20 sounds. These 28 sounds form the first part of each sound sequence (rand). From this pool of 20 sounds, a sound sequence with a repeating single frequency (regular, reg) and sound sequences with regularly ris-

ing (ris) and decreasing (dec) frequencies were formed. These three patterns were added to a random sequence of 28 tones, forming rand-reg, rand-dec, and rand-ris. Finally, 20 sounds in the pool were randomly sequenced, added to initial rand stimuli, and rand only stimuli were created.

For participant selection, pure-tone audiometry between frequencies of 0.25–8 kilohertz (kHz); speech discrimination tests and acoustic reflex test between frequencies of 500 Hz and 4000 Hz; reflex decay tests at 500 Hz and 1000 Hz; and MLD test were conducted. For ruling out any cognitive disorder, the Turkish version of Mini Mental Test was applied^[20].

Participants satisfying the selection criteria were presented with phonetically balanced 50 word lists at a signal to noise ratio (SNR) of -5 dB and -10 dB via a MP3 player connected to the audiometer^[22]. The level of speech was kept at 65 dB SPL, and the level of speech noise (in-built function of the audiometer) was manipulated. For each noise condition, 50 words were presented, and two points were given for each correct response. After SIN scores were rank ordered, high and low performance groups were formed on the basis of the median score.

Evoked potential recordings were conducted in an acoustically/electrically shielded chamber with a Neuroscan 4.3 system (Neuroscan; Compumedics, Charlotte, USA) via standard 20 channel EEG caps; reference electrodes were placed at earlobes. The experiment consisted of passive and active phases. In the passive phase, the participants watched a subtitled movie, and in the active phase (after a short training session for explaining the regularities), they were asked to press a button immediately when a regularity was detected. All the participants were subjected to passive and active listening phases consecutively. Four stimuli were presented in random order 30 times in each of the four blocks in the active and passive phases. After each block, a short break was given depending on request; a 10-min break was given between the phases.

Raw EEG recordings were band-pass filtered at 0.5–30 Hz and notch filtered at 50 Hz and epoched for 1800 ms via EEG LAB and ERP LAB software^[23,24]. The artefact rejection threshold was ± 100 μ v. Linked ear reference was used.

Each participant's averaged waveforms were visually analyzed for a peak with a negative deflection at the latency between 1000 ms and 1200 ms, which is the latency range of the N1 response time locked to the onset of regularity stimuli.

Two criteria for determining a negative deflection as a regularity detection response were (1) the existence of a positive deflection in the mean global field power (MGFP) waveform at the latency of the peak and (2) the peak in the waveform formed, with ± 2 standart deviation (SD) of the actual waveform voltage deflections being under the 0 point in y axis. Figure 1 shows the average and MGFP waveforms of a participant for Rand-reg stimuli from the Cz electrode. Statistical analysis for both behavioral and electrophysiological findings was conducted using Statistical Package for the Social Sciences (SPSS) (SPSS; IBM, USA).

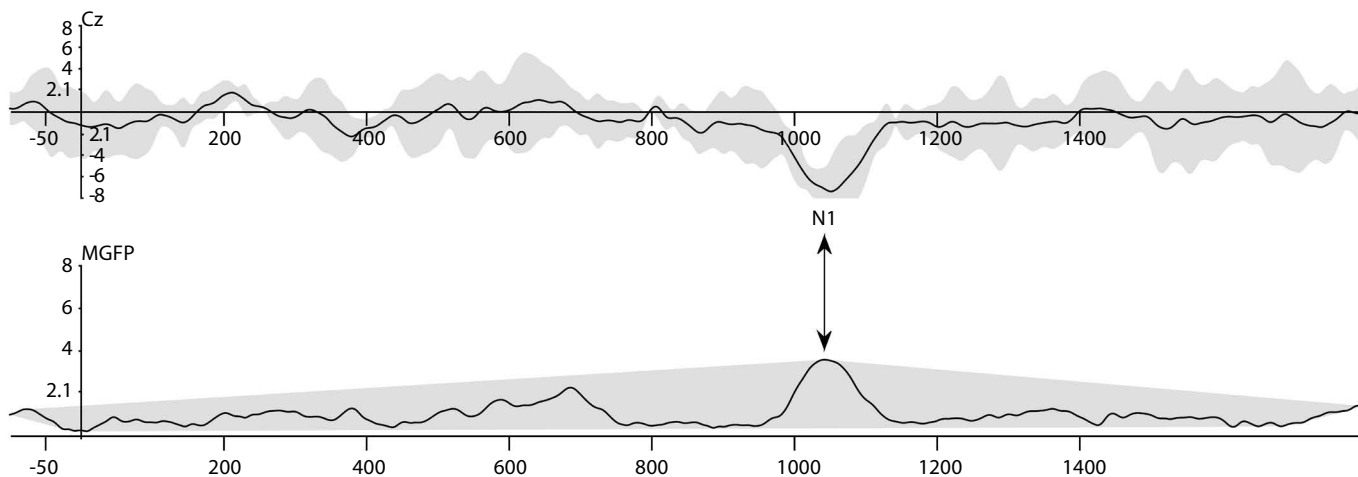


Figure 1. Example of waveform analysis from a single participant in the study. Upper waveform is the average waveform and lower is the mean global field power waveform
 Cz: central zero electrode; MGFP: mean global field power

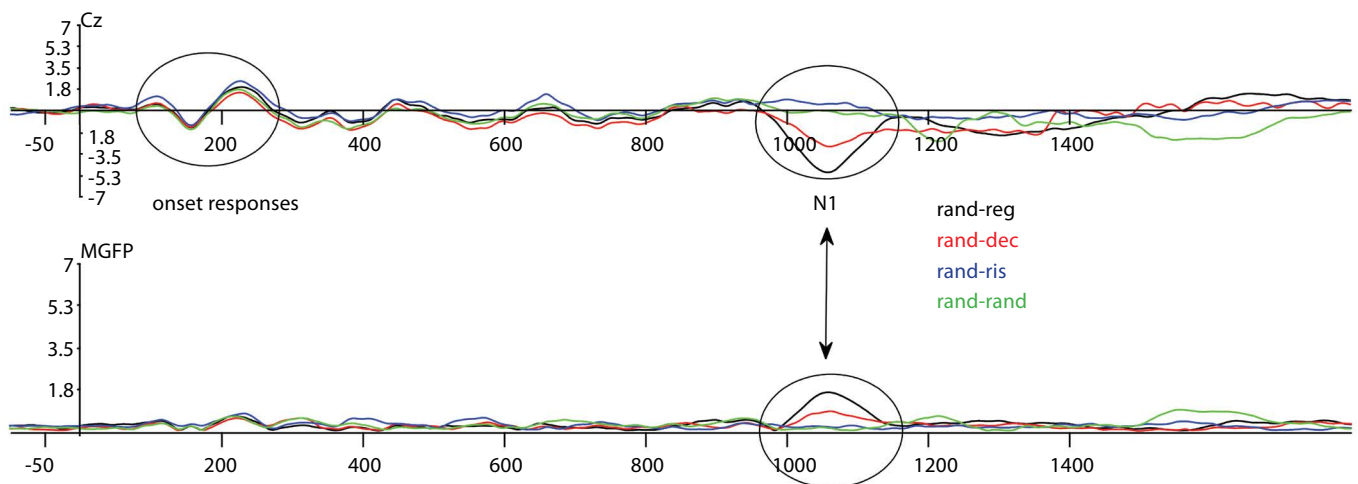


Figure 2. Grand average waveforms of evoked potentials in passive phase. Black shows rand-reg responses, red shows rand-dec responses, blue shows rand-ris responses and green shows random only stimuli responses.
 Cz: central zero electrode; MGFP: mean global field power; rand-reg: random to regular transition; rand-dec: random to decreasing transition; rand-ris: random to rising transition; rand-rand: random only

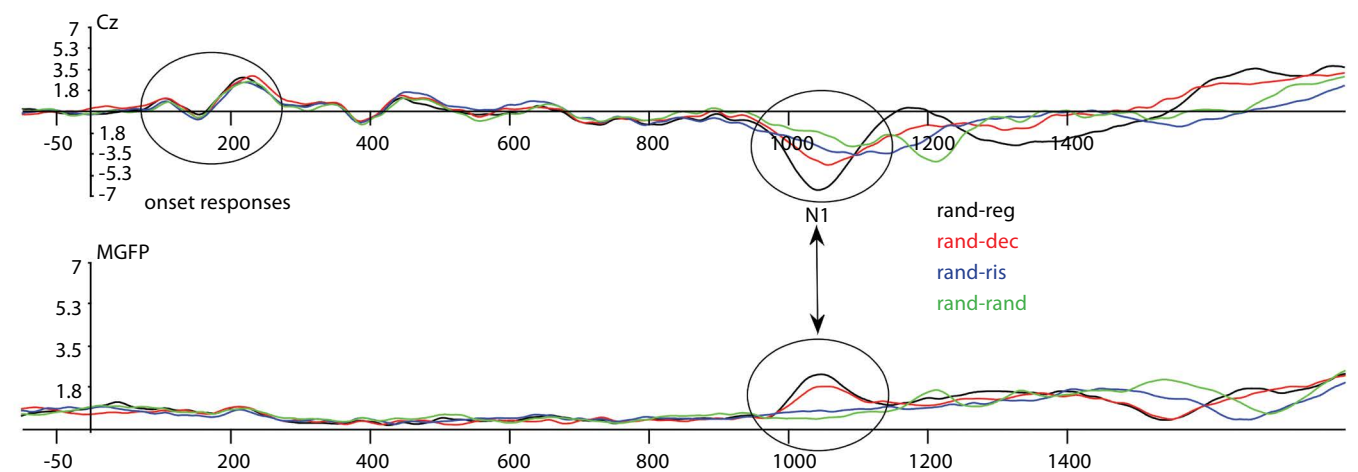


Figure 3. Grand average waveforms of evoked potentials in active phase. Black shows rand-reg responses, red shows rand-dec responses, blue shows rand-ris responses and green shows random only stimuli responses.
 Cz: central zero electrode; MGFP: mean global field power; rand-reg: random to regular transition; rand-dec: random to decreasing transition; rand-ris: random to rising transition; rand-rand: random only

RESULTS

Two groups with different SIN performance were formed on the basis of the SIN test score at -5 dB SNR (sin_5) of participants because the distribution of the SIN test score at -10 dB SNR (sin_10) was mostly in the low score region owing to the highly demanding characteristic of the task. Participants with scores higher than the median (m=28) were assigned to the top group (N=10), while those with scores equal to or lower than the median were assigned to the bottom group (N=12).

The Mann-Whitney Test was utilized for between-group comparisons of “number of stimuli evoking no transition response” (missing), “number of regularity stimuli not detected” (false_neg), “number of stimuli falsely detected as a regularity” (false_pos), and sin_5; the groups significantly differed in terms of only sin_5 (U=0.000, p=0.006), as shown in Table 1.

Grand average waveforms (GAWs) of evoked potentials in passive and active phases are shown in Figure 2 and Figure 3, respectively. Clear-onset responses to each of the four stimuli were observed; transition responses (N1) were only observed in rand-reg and rand-dec, and a questionable peak was observed in rand-ris in the active phase.

The t-test for independent groups showed no significant difference between groups in terms of latency and amplitudes in the active phase (p>0.05). In the passive phase, the test of normality was not applicable because of a low number of observations for rand-ris responses; group differences were not analyzed. While searching for the reason for this, the slope of rand-ris stimuli was recognized to be different from that of rand-dec stimuli, making the comparison of responses problematic. Hence, rand-ris responses were removed from further analysis. In the passive phase, between-group differences were re-analyzed for rand-dec and rand-reg responses, and no significant difference was observed (p>0.05). Pearson correlations showed a significant negative correlation between rand-dec response amplitudes in the active phase and sin_5 (r=-0.501, p=0.029), indicating that the N1 response amplitude increases with increasing SIN performance.

Paired-sample t-test showed a significant difference between rand-reg and rand-dec response amplitudes in the active and passive phases [t(18)=-2.30, p=0.033 and t(16)=-3.69, p=0.002, respectively]. Rand-reg responses in active (M=-6.51, SD=1.98) and passive phases (M=-5.53, SD=1.98) were greater than rand-dec responses in active (M=-5.36, SD=1.45) and passive phases (M=-3.98, SD=0.994).

Latencies were also significantly different between these two stimuli in active and passive phases [t(18)=-3.38, p=0.003 and t(16)=-2.47, p=0.025, respectively) Rand-reg responses had a shorter latency in active (M=1042, SS=17.14) and passive (M=1056, SS=17.51) phases than rand-dec responses in active (M=1061, SS=29.43) and passive (M=1096, SS=71) phases.

Factorial analysis of variance (ANOVA) for comparing peak amplitudes at anterior-posterior (Fp1, Fp2, F3, Fz, F4 and C3, Cz, C4) and left-central-right (Fp1, F3, C3; Fz, Cz; Fp2, F4, Cz) electrodes and the group variable showed a significant main effect of anterior-posteri-

Table 1. Between group comparison of missing, sin_5, false_neg, and false_pos variables

Variable	N	SS	Md	Z	p
Missing^a					
Top	10	0.95	1	-0.66	0.507
Bottom	12	1.29	1		
Sin_5^b					
Top	10	14.1	36	-3.98	0.006*
Bottom	12	7.47	24		
False_neg^c					
Top	10	4.52	1.5	-0.47	0.640
Bottom	12	2.89	2		
False_pos^d					
Top	10	4.29	4	-1.81	0.070
Bottom	12	1.38	0.5		

*p<0.05
^anumber of stimuli evoking no transition response
^bspeech-in-noise test score at -5 dB SNR
^cnumber of regularity stimuli not detected
^dnumber of stimuli falsely detected as a regularity

or [F(1, 458)=49.85, p<0.001] electrode sites. Anterior electrodes had higher amplitudes (M=-6.96, SD=3.04) than posterior electrodes (M=-5.31, SD=1.72), without significant interaction effects (p>0.05).

DISCUSSION

Understanding SIN is a complicated mechanism and a common problem among individuals with different health conditions (hearing loss, aging, and others) [25]. Daily life communication rarely occurs under appropriate listening conditions, and listeners are often surrounded by noise [26]. Normal-hearing individuals may somehow accomplish speech understanding in noise, but it is a common complaint; investigating this complicated mechanism by both behavioral and electrophysiological means is stated to be important [27]. In terms of electrophysiological means, cortical representations of speech sounds in noise has been investigated by speech-evoked cortical responses and speech-sound evoked mismatch negativity (MMN) responses in noise, the results of which have shown changes in the cortical representations of speech sounds in noise in comparison with silence [12-14, 28, 29].

In the present study, cortical representations of auditory regularities, the detection of which is thought to be related to SIN abilities, was compared between two groups with different SIN scores. If clear differences were found in parameters related to evoked potentials between SIN groups, the test was planned to be applied to clinical cases of SIN problems, e.g., hearing-impaired individuals, normal-hearing individuals with SIN problems, cochlear implant (CI) users with SIN complaints, children with developmental dyslexia, individuals with defective reading and phonological awareness skills, individuals with learning problems, and individuals with autism, in future studies to reveal which mechanism of SIN process is defective [30-38, 13, 39, 40].

Despite the SIN difference between groups, evoked potentials were not significantly different, contrary to our hypothesis. In fact, the lack

of relation between a perceptual ability and related evoked potentials had previously been observed [26, 8]. Despite finding no group difference, which may be related to our relatively small study sample, rand-dec response amplitudes in the active phase were significantly higher in three highest performers of the top group ($M=-7.50$, $SD=0.90$) than in the three lowest performers of the bottom group ($M=-4.69$, $SD=0.82$) [$t(3)=3.62$, $p<0.05$], and cortical representations of rand-dec regularities were more robust in individuals with high SIN ability. These results show that cortical potentials evoked by rand-dec stimuli are promising for distinguishing between individuals with different SIN abilities, particularly when there is a significant gap between SIN performances.

Finding no between groups difference may be because of the dec section of the stimuli. One of the expectations was that the dec frequency pattern would be similar to an intonation pattern used in daily speech, such as while making a statement. Intonation patterns correspond to F_0 trajectories, tracking of which is one of the mechanisms involved in extracting the target message in the presence of masking sounds [16]. It was expected that the dec part of our stimuli may be detected like an intonation pattern (an auditory regularity). In fact, the dec part may have involved a faster rate of change than F_0 patterns in daily speech, which are slow [41]. Therefore, the dec section of the stimulus may not have been represented as robustly as an intonation pattern, failing to show a relation between its cortical representation and SIN ability.

Another possibility is that the detection of regularities had been very easy for the participants; cortical representations had not been different. In fact, groups were not different on behavioral regularity detection (false_pos and false_neg), which may be leading to similar levels of robustness for representations. Besides, our stimulus may not be reflecting the appearance of auditory regularities in real life, where these regularities are masked by the other sounds. In contrast, in our paradigm, regularities appear without any concealment; therefore, we may have not tested auditory regularity detection in the way in which it takes part in SIN. Manipulation of the stimuli so that the regular part is concealed by other sounds is suggested.

One can argue that the transition responses of dec stimuli may be responses evoked by the frequency ramp corresponding to this part, which is known to evoke N1 [7, 8]. A point of difference between our paradigm and the ramping stimuli is that in rand-dec stimuli, the change starts from not a single ongoing sound like in ramping stimuli but from a set of random frequency sounds. N1 responses evoked by ramping stimuli are due to a change in the frequency of ongoing stimulation, but N1 responses evoked by dec stimuli are due to the detection of a regularity. Moreover, latencies of N1 in our study are longer than those of ramp responses, which may be showing that some higher level processes in the auditory system are functioning (possibly regularity detection).

It may be argued that the frequency difference between the last few sounds of random part and the first sound of reg and dec parts have evoked the N1 responses. When a series of sounds with the same frequency are presented sequentially, the emergence of a sound with a different frequency evokes a larger N1 response (But-

ler, 1968; Picton, Campbell, Baribeau-Baun & Proulx, 1978; cited in Näätänen and Picton [12]). This may be speculated to have occurred because of the frequency difference between the last few sounds of rand and the first sound of reg and dec. However, the N1 latencies in our study are higher than those evoked by a frequency change, a sign that different mechanisms than ramp detection are involved. Besides, if the N1 response was because of a frequency change, the N1 amplitudes of rand-reg and rand-dec responses would have been similar; the frequency differences between rand and dec/reg parts are the same; yet, rand-reg amplitudes are significantly larger. This may be because the reg part is easier to detect than the dec part (the result of which is observed in enhanced cortical representations of the reg part; therefore, the amplitudes of N1 are higher), the detection of which may require increased number of stimuli (similar to discussed by Chait et al. [17]) leading to prolonged latencies for rand-dec transition.

Our recommendation at this point would be to make some changes in the stimuli, like making the ris part of the rand-ris stimuli have the same slope as the dec part and concealing the regularities with random sounds and applying the paradigm to larger study samples than those included in the present study for enhanced face validity. Next, application of the paradigm to individuals with clinical-level SIN problems is suggested. By this, the stage at which the complicated process of SIN is defective can be revealed. The results of these experiments may be used for rehabilitative interventions (regularity detection training). In addition, evoked responses may be utilized for tracking how regularity representations change with training. Moreover, if regularity representations are found to be defective in people using auditory prostheses, sound processing strategies for enhancing regularity detection may be developed.

Ethics Committee Approval: Ethics committee approval was received for this study from the ethics committee of Hacettepe University with registration code GO 14/406-09.

Informed Consent: Written informed consent was obtained from patients who participated in this study.

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Author Contributions: Concept - M.Y., A.G.G., S.A.; Design - M.Y., A.G.G., S.Y., S.A.; Supervision - A.G.G., S.Y., S.A.; Resources - M.Y.; Materials - M.Y., S.A., S.Y.; Data Collection and/or Processing - M.Y.; Analysis and/or Interpretation - M.Y.; Literature Search - M.Y.; Writing Manuscript - M.Y., S.A. Critical Review - S.A., S.Y., A.G.G.

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