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ORIGINAL ARTICLE

Frequency Discrimination: Frequency Modulated Difference Limen or Auditory Steady State Response?

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Objective: FFrequency discrimination is a fundamental auditory process underlying more complex auditory tasks. Subjective methods are usually used to measure frequency discrimination. This research was designed to study frequency discrimination in normal hearing subjects and those with sensorineural hearing loss.

Materials and Methods: This research included two groups: control group (GI) which is composed of 30 normal hearing adults. The other is the study group (GII) which included 33 subjects with sensorineural hearing loss. Frequency discrimination was assessed using two different procedures: 80Hz-Auditory steady state response and Frequency Modulated Difference Limen.

Results: Auditory steady state response amplitude showed no significant difference between different frequencies in both groups. However, Frequency Modulated Difference Limen test showed gradual increase in the frequency difference required for discrimination as a function of increasing carrier frequency in both groups.

Conclusion: Although Auditory steady state response had been suggested as a new tool for assessing frequency discrimination, the psychophysical method such as Frequency Modulated Difference Limen still has a major role for such purpose.

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Introduction

Frequency discrimination, occasionally referred to as pitch perception, is a fundamental auditory process underlying more complex auditory tasks, such as speech comprehension and understanding [1]. The importance of discrimination of sound frequency resides in its necessity for providing prosody (intonation) in languages. The mechanisms of pitch perception have been a matter of debate for a century [2]. However, two theories can be used to explain frequency perception within the auditory system. In the first theory, frequency is encoded by the discharge pattern in the primary auditory fiber. This discharge pattern is phase-locked to a particular phase of sound vibration. Place theory is the second theory explaining frequency perception. In this theory, specific parts of the basilar membrane vibrate in response to different frequencies. Moreover, frequency discrimination also exists at central levels, where stimulation of a particular place along the basilar membrane evokes response in particular auditory neurons in the brain [3].

Two methods are commonly used to measure frequency discrimination subjectively. These are; difference limen for frequency, i.e., discrimination of successive steady tones with slightly different frequency, and frequency modulation difference limens (FMDLs), i.e., discrimination of frequency modulated tones [4]. Frequency difference limen is the smallest change in frequency that can be detected subjectively. It generally equated with the concept of the just noticeable difference in frequency [5,6].

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Auditory Steady State Response (ASSR) is an electrophysiological response to repeated auditory stimuli presented at a high repetition rate. It relies on statistical measures to determine when and if a response is present [7]. It is specific to the pitch of a sound and it thus reflects that sounds are perceived by the brain. Auditory Steady State Response demonstrates how the brain follows a stimulus or how the stimulus derives a response. Modulated stimuli used for eliciting ASSR are useful in assessing how the brain can detect changes in frequency and amplitude [8]. Furthermore, most studies of ASSR have used modulated tones because they have good frequency-specificity [9].

Frequency modulated tones (FM) show dynamic changes in frequency without necessarily affecting the instantaneous amplitude. They are usually determined by two basic components; the carrier frequency and the modulated rate [10].

Many studies examining frequency discrimination have yielded conflicting results. This could be due to several reasons; including using different tasks for frequency discrimination (simple vs. complex), normal hearing subjects vs. subjects with different causes and configurations of hearing loss (peripheral versus central). Moreover, examining frequency discrimination by sound field or binaural presentation yielded also different results from monaural stimulation [1].

In a trial to study frequency discrimination in different types of hearing loss, we decided to test also normal hearing subjects. Two questions were raised while designing this research. The first question was; is there a difference between subjective frequency discrimination and objective frequency discrimination? The second question was; is there a relation and/or a correlation between the FMDL test (as a subjective test for frequency discrimination) and the ASSR (as an objective tests for frequency discrimination) since they both measure frequency discrimination? The aim of research was twofold. The first was to compare frequency discrimination in normal hearing subjects and those with hearing loss. While, the second aim was to compare frequency discrimination in subjects with mild and moderate hearing loss. This was done using frequency modulated subjective and objective methods.

Materials and Methods

Sixty three subjects participated in this research. Those subjects were patients or volunteers from relatives of patients attending the Audiology Unit. They were classified into:

1- Control group: Thirty normal hearing adults (13 females and 17 males) with their age range of 25-45 years. The inclusion criteria included peripheral hearing threshold better than 25dB HL in the frequency range from 250-8000Hz. As well as normal middle ear function demonstrated by type A Tympanogram & proportionate acoustic reflex threshold. Subjects were recruited from the Out-Patient Clinic of Audiology unit at Tanta University Hospital. They all had no history of hearing difficulties, neurological problems or any endocrinal complaints.

2- Study group: Included 33 subjects with hearing loss (16 females and 17 males) with their age range of 30-48 years. They were 18 subjects (11 females and 7 males) with mild sensorineural hearing loss and 15 subjects (6 females and 9 males) with moderate sensorineural hearing loss. The hearing loss was flat in all subjects, with no more than 10-15dB difference between any adjacent frequencies. They all had bilateral type A tympanograms with acoustic reflex threshold within the expected range.

All subjects included in this study were submitted to the following

1- 80Hz-Auditory Steady State Response (ASSR) test: Four frequencies with eight different modulation rates were tested from each ear separately. Each frequency was tested alone. The stimuli were frequency modulated (FM) and the modulation rates were: 77, 85, 93 and 101Hz in the right ear and 79, 87, 95, and 103Hz in the left ear for the carrier frequencies 500, 1000, 2000 4000Hz respectively. Those modulation rates were the default specification of Smart EP-Intelligent Hearing System. The number of sweeps at each stimulus frequency ranged from 100-200. Test stimuli were presented via ER3A insert-phone calibrated in hearing level at 40dBSL (re-PTA). ASSR was acquired using 2-channel recordings using four electrodes in the

following montage: positive at Fz (high forehead), ground at lower forehead (Fpz), and two negative electrodes placed at both mastoids (M1 and M2). Subjects were seated in a relaxing and comfortable chair in a quiet room.

2- Frequency Modulated Difference Limen (FMDL):

A clinical adaptation of the frequency discrimination procedure was used for Frequency Modulation (FMDLs) on Interacoustic AC5 audiometer. A difference limen frequency test was intended to establish the smallest change in frequency modulation that can be recognized. Instructions were provided as follows: you are going to hear two tones of different pitch, you will respond verbally until you hear one tone only. The signals were delivered monaurally via earphone at 40dBSL. Difference limen for frequency was measured at 500Hz, 1KHz, 2KHz and 4KHz. Familiarization of the subject to discriminate the frequency modulation was done at 5%, which is normally clearly audible. Subjects were first trained to listen for a difference between two tones with a widely differing modulation (0% FM and 5%FM) until they reached a 100% criterion of consistent responses. Next, subjects listen in the test procedure to a sequence of two tones: unmodulated and tone varying in modulation (5, 3, 2, 1, 0.8, 0.6, 0.4, 0.2, and 0%). Subjects were required to report an audible difference between modulated and unmodulated tones by saying (yes). Modulation was varied adaptively, i.e., decreased after three (yes) responses and increased after one (no) response. Frequency modulation difference limen (FMDL) was defined as the smallest detectable difference in frequency modulation between modulated and unmodulated standard tone [11]. Scoring was done by calculating DL as percentage referenced to the primary signal which was then, converted into frequency difference in Hz [6].

The procedures were explained to all participants in this research who gave us their consent to participate in it. This research had been carried out in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki, JAMA 2000; 284:3043–3049).

Statistical Methods

Statistical analysis was done using SPSS-V15 package. Un-Paired-Sample T-test was used to compare the mean of age, ASSR amplitude and FMDL between both groups (GI and GII). Comparison was also done between control (GI) and each subgroup (GIIa and GIIb). Then, both subgroups were compared with each other (GIIa and GIIb).

Results

This study included 63 subjects which were divided into two groups: the control group (GI) which included 30 subjects with normal peripheral hearing. Their mean age was 39.1±4.6 years. On the other hand, the study group (GII) included 33 subjects with SNHL. Their mean age was 40.1±4.9 years. GII was further divided into two subgroups: GIIa which included 18 subjects with mild SNHL and GIIb which included 15 subjects with moderate SNHL. Their mean age was 39.5±3.9 years and 40.2±2.7 years in GII and GIIb respectively. There was no statistical significant difference between the age in the three groups included in the study ($p>0.05$). As regard hearing threshold levels, the mean was 18.3±.35, 36.8±2.8 and 46±5.7dBHl in GI, GIIa and GIIb respectively (Table 1).

Group I (GI): Auditory Steady State Response amplitude showed no significant difference between different frequencies. However, FMDL test showed gradual increase in the frequency difference required

Table 1. Mean±SD of hearing thresholds in different groups at different frequencies

Groups	250Hz	500 Hz	1,000Hz	2,000Hz	4,000Hz	8,000Hz	Mean± SD
GI	15±3.5dB	10±2.8dB	10±4.3 dB	15.3±2.6dB	15.3±3.2dB	17.6±4.2dB	18.3±.35dB
GIIa	35.2±3.3dB	32.6±4.3dB	29.3±5.8 dB	28.6±5.9dB	30.2±5.6dB	40.3±3.5dB	36.8±2.8dB
GIIb	48.11±5.6dB	43.63±4.2dB	50.9±4.7 dB	49.32±2.3dB	41.26±8.5dB	44.32±3.9dB	46±5.7dB

for frequency discrimination as a function of increasing carrier frequency from 500Hz to 4000Hz. In Group II (GII), both ASSR amplitude and FMDL test showed similar result to that found in GI (Table 2; Figures 1 and 2).

The comparison between both groups (GI and GII) revealed that ASSR amplitude showed no significant difference. As regard FMDL test, there was a significant difference between both groups at all carrier frequencies. In other words, subjects with SNHL required greater frequency difference to discriminate between frequencies. This difference increases with increasing the carrier frequencies (Table 2; Figures 1 and 2).

Table 2. Mean±SD of ASSR amplitude (in μv),andFMDLs (in Hz) in both groups (I and II) results of their comparison

Test	Freq.	Groups	Mean	t. test	p value
ASSR	500Hz	GI	.114±.029 μv	0.147	0.884
		GII	.109±.014 μv		
	1,000 Hz	GI	.100±.012 μv	1.991	0.060
		GII	.150±.021 μv		
	2,000 Hz	GI	.114±.021 μv	1.101	0.271
		GII	.146±.019 μv		
	4,000 Hz	GI	.154±.035 μv	0.270	0.970
		GII	.141±.027 μv		
DLF	500 Hz	GI	5.93±.380 Hz	6.592	0.001*
		GII	9.39±.361 Hz		
	1,000 Hz	GI	9.60±.148 Hz	14.772	0.001*
		GII	18.78±.576 Hz		
	2,000 Hz	GI	18.0±.498 Hz	12.17	0.001*
		GII	36.36±1.363 Hz		
	4,000 Hz	GI	34.66±1.038 Hz	7.562	0.001*
		GII	67.87±4.07 Hz		

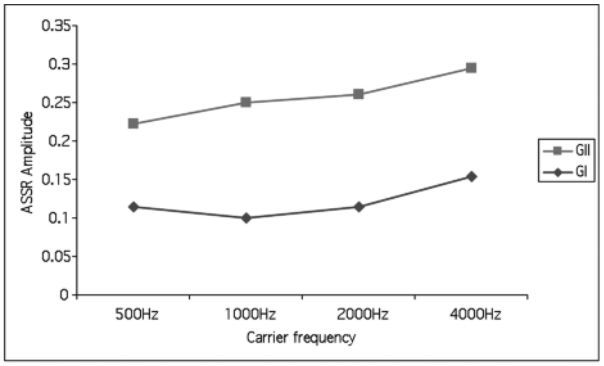

Figure 1. Mean of ASSR amplitude (in μv) in both groups at different carrier frequencies

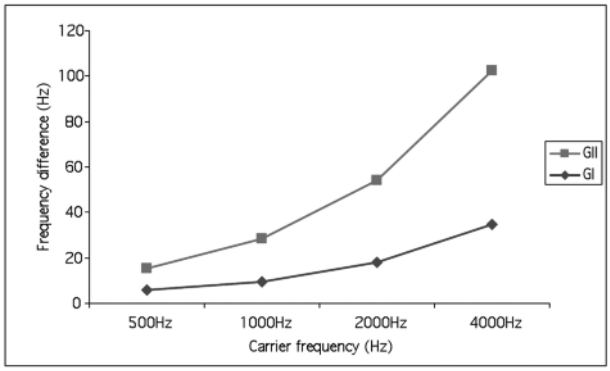

Figure 2. Mean of FMDLs in Hz in both groups at different carrier frequencies

Comparing GI with GIIa and GIIb showed no significant as regard ASSR amplitude ($p<0.05$). As regard FMDL test, there was a significant increase in frequency difference in GIIa and GIIb as the carrier frequency increase ($p<0.05$) (Tables 3-5; Figures 3 and 4).

Table 3. Mean±SD of ASSR amplitude (in μv),FMDLs (in Hz) in GI subgroup GIIa results of their comparison

Test	Freq.	Groups	Mean±SD	t. test	p value
ASSR	500Hz	GI	.114±.029 μv	0.184	0.855
		GIIa	.106±.021 μv		
	1,000 Hz	GI	.100±.012 μv	1.99	0.065
		GIIa	.167±.033 μv		
	2,000 Hz	GI	.114±.021 μv	1.057	0.296
		GIIa	.152±.029 μv		
	4,000 Hz	GI	.154±.035 μv	0.010	0.989
		GIIa	.154±.041 μv		
FMDL	500 Hz	GI	5.93±.380 Hz	5.381	0.001*
		GIIa	9.44±.555 Hz		
	1,000 Hz	GI	9.60±.148 Hz	21.007	0.001*
		GIIa	19.44±.555 Hz		
	2,000 Hz	GI	18.0±.498 Hz	14.771	0.001*
		GIIa	37.7±1.52 Hz		
	4,000 Hz	GI	34.6±1.03 Hz	6.211	0.001*
		GIIa	66.6±6.46 Hz		

Table 4. Mean±SD of ASSR amplitude (in μv)and, FMDLs (in Hz) in GI subgroup GIIb results of their comparison

Test	Freq.	Groups	Mean±SD	t. test	p value
ASSR	500Hz	GI	.114±.029 μv	0.026	0.936
		GIIb	.112±.020 μv		
	1,000 Hz	GI	.100±.012 μv	1.272	0.210
		GIIb	.131±.024 μv		
	2,000 Hz	GI	.114±.021 μv	0.696	0.325
		GIIb	.138±.024 μv		
	4,000 Hz	GI	.154±.035 μv	0.503	0.253
		GIIb	.126±.035 μv		
FMDL	500 Hz	GI	5.93±.380 Hz	5.420	.0.001*
		GIIb	9.33±.454 Hz		
	1,000 Hz	GI	9.60±.148 Hz	10.819	0.001*
		GIIb	8.0±1.06 Hz		
	2,000 Hz	GII	18.0±.498 Hz	9.273	0.001*
		GIIb	34.66±2.36 Hz		
	4,000 Hz	GI	34.66±1.038 Hz	9.273	0.001*
		GIIb	69.3±4.72 Hz		

Table 5. Mean±SD of ASSR amplitude (in μv),and FMDLs (in Hz) in subgroups GIIa GIIb results of their comparison

Test	Freq.	Groups	Mean±SD	t. test	p value
ASSR	500Hz	GIIa	.106±.089 μv	0.219	0.325
		GIIb	.112±.078 μv		
	1,000 Hz	GIIa	.167±.143 μv	0.825	0.236
		GIIb	.131±.092 μv		
	2,000 Hz	GIIa	.152±.127 μv	0.346	0.732
		GIIb	.138±.094 μv		
	4,000 Hz	GIIa	.154±.174 μv	0.503	0.475
		GIIb	.126±.136 μv		
FMDL	500 Hz	GIIa	9.44±2.357 Hz	0.151	0.881
		GIIb	9.33±1.75 Hz		
	1,000 Hz	GIIa	19.44±2.35 Hz	1.258	0.218
		GIIb	18±4.140 Hz		
	2,000 Hz	GIIa	37.7±6.46 Hz	1.141	0.262
		GIIb	34.6±9.154 Hz		
	4,000 Hz	GIIa	66.6±27.439 Hz	0.231	0.750
		GIIb	69.3±18.30 Hz		

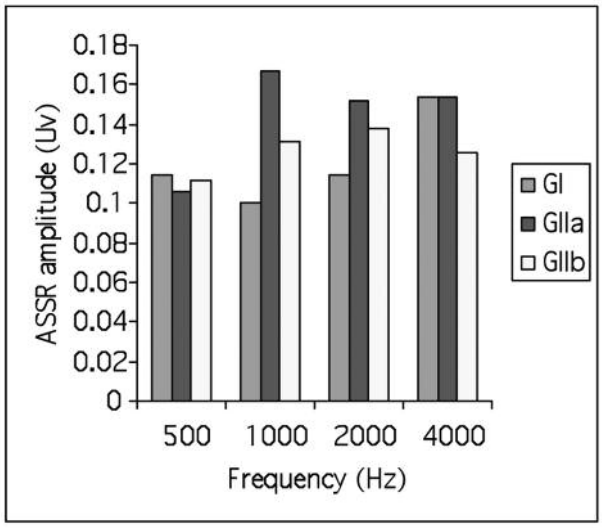

Figure 3. Mean of ASSR amplitude in both group I and subgroup GIIa GIIb at different frequencies

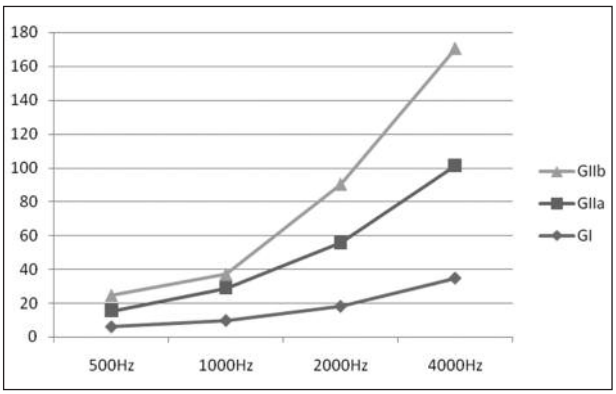

Figure 4. Mean of FMDL (in Hz) in group I and subgroup GIIa GIIb at different frequencies

Discussion

Psychophysical measures in human revealed that low-frequency amplitude modulation features are crucial for speech identification and recognition [12-13], and frequency modulated cues are important in speech recognition, particularly in noise [14]. Furthermore, these temporal modulation features are known to be encoded in the auditory system and their precise timing of information processing is preserved throughout the ascending auditory pathways [15-18].

Pitch perception or frequency discrimination, has been studied for more than 150 years but, its underlying mechanism/mechanisms still remain elusive [19]. In speech and music, complex tones are perceived as having a single 'pitch' and extraction of this pitch is crucial in the perception of speech intonation and musical melody [20].

In this research, frequency discrimination was assessed using two procedures. The first was the frequency modulation difference limen (FMDL) which can be used to measure the smallest change in frequency subjectively [4]. The second was ASSRs which can be used to assess the ability of the cochlea and brainstem to discriminate sounds that are important for speech discrimination [8].

Results of ASSR and FMDLs showed similar trend in normal hearing subjects and those with hearing loss. In both groups, ASSR amplitudes did not show any significant variation with the change of carrier frequency. On the contrary, the mean FMDLs increased gradually with increasing frequency of the carrier tone in either normal hearing and those with hearing loss. This result agreed with the results of Propst et al., [21] and Demany and Semal [22] in spite of using different methodological procedures.

Comparing the results of normal hearing subjects with those having SNHL revealed that ASSR amplitude had no significant difference. Meanwhile, FMDLs results revealed that subjects with hearing loss required greater modulation differences than normal for frequency discrimination. Furthermore, these differences increased with increasing the carrier frequencies. This finding supports the hypothesis that FMDL enhancement occurs due to injury-induced central reorganization in the auditory system [23].

Comparing subjects with mild SNHL with those with moderate SNHL revealed no significant difference in both ASSR and FMDLs. This result indicated that the main difference is present between normal hearing subjects and those with sensorineural hearing loss and is not related to the degree of hearing loss.

Generally, results of ASSR in our research are not consistent with John et al., [24] who reported that ASSR amplitude are higher for mid-frequencies (1,000-2,000Hz). However, those authors used multiple ASSR recording which is quite different from our procedure where each ear and each frequency were tested alone. It is known that the effect of modulation rate on ASSR amplitude varies with the carrier frequencies. However, John and Picton [25] found no significant interaction between carrier frequencies (500-6,000Hz) and modulation rates (78- 96Hz).

At the same time, FMDLs vary largely as a function of the carrier tone, modulation characteristics as well as the complexity of the stimuli [26-27]. Furthermore, FMDLs results may also vary because of presentation mode, peripheral hearing status and central auditory nervous system pathology especially cortical one which can affect frequency discrimination, particularly if the damage occurs in the right hemisphere [1].

Results of FMDLs could be explained by phase-locked excitation of the cochlear nerve which allows for temporal coding to occur only for low frequency stimuli (below approximately 1,500 to 3,000Hz) in normal-hearing individuals. At higher frequencies, significant phase-locking does not occur and processing of such information is limited to only place or excitation pattern [28-29]. Frequency modulated difference limen results are also dependent on the modulation rates. In other words, at low modulation rate (5-80Hz), frequency modulation detection is temporally based. While at higher modulation rates, it is likely to be performed by a spectrally based mechanism which requires the ear to resolve sidebands in the frequency domain. Lack of temporal coding at higher frequencies may be one reason why poorer frequency discrimination occurs with increasing frequency of carrier tones in individuals with normal hearing [10]. Lack of temporal coding at higher frequencies may be one reason why poorer frequency discrimination occurs with increasing frequency of

carrier tones in individuals with normal hearing. Since the higher frequency used in this research is still considered a lower frequency than that used in Propst et al.'s [21] study, we can apply the same explanation.

Pitch perception is dependent on excitation pattern along the basilar membrane (place theory) and the exact timing of the neural impulses. Frequency discrimination assumed to be related to the sharpness of the excitation pattern [30]. Hence, cochlear damage, which results in broadening of this excitation pattern and abnormal phase locking, should result in poor frequency discrimination [31]. Hearing impaired people appear to be less sensitive to high rates of modulations than normal-hearing listeners. This could be explained by more affection in the high frequency region [32]. Difference limens for frequency (DLFs) are adversely affected by cochlear damage (increased DLFs) [33]. This abnormality could be explained by abnormality in place of excitation, loss of neural synchrony (phase locking) of the auditory nerve. It could be also due to time differences arising from the propagation time of traveling wave on the basilar membrane. This peripheral affection results in affection of central mechanisms involved in the analysis of phase locking information with disruption of temporal processing [34].

The wide variability of the results of difference limen in this research obtained for normal subjects, suggests that additional factors may have affected frequency discrimination. Although both frequency modulated difference limen and auditory steady state response measure frequency discrimination, there was no significant relation between both procedures in normal hearing subjects or in those with SNHL. This does not mean that we are chasing irrelevant information and finding such relation may need certain methodology to be apparent. This can be through using complex stimuli, complex procedure or subjects with different configuration & causes of hearing loss. So, we can conclude that although auditory plasticity took place after hearing loss, yet, cochlear processing still affected. Recent electrophysiological methods have been suggested as a new tool for assessing frequency discrimination. However, the psychophysical method still has the upper hand and cannot be substituted yet with electrophysiological methods.

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