Int. Adv. Otol. 2010; 6:(1) 74-82

ORIGINAL ARTICLE

Enhancement of Speech Intelligibility in Digital Hearing Aids Using Directional Microphone/Noise Reduction Algorithm

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Objective: We aims to detect the efficacy of directional microphone when combined with noise reduction algorithm in improving speech intelligibility in noisy environments for hearing impaired subjects.

Materials and Methods: Twenty adult subjects with bilateral symmetrical sensory neural hearing loss of moderate to moderately severe degree were examined. Aided assessment was done in two settings using BTE digital hearing aid. First setting included: evaluation using noise reduction algorithm alone. Evaluation in the second setting was done using both noise reduction algorithm and directional microphone. Aided evaluation consisted of speech discrimination scores in quiet and speech in noise test in different noise scenarios. Just follow conversation test was done to detect the least signal to noise ratio a subject can tolerate in each of the two settings. The subjective impression of the patient was assessed by a modified questionnaire for hearing aid assessment.

Results: Investigation showed statistically significant improvement of aided speech discrimination scores in noise in the second aided setting when speech was at zero degree azimuths and noise was at zero and 180 degrees azimuth.

Conclusion: Directional microphone when combined with noise reduction algorithm in a digital hearing aid, adds benefit in improving speech intelligibility for patients with moderately-severe sensory neural hearing loss whatever the duration of the hearing loss.

Submitted : 03 August 2009 *Accepted : 01 October 2009*

Introduction

Understanding speech in a moderately noisy environment occurs because speech is a highly redundant signal. Normally, if part of speech signal is masked by noise other parts of the speech signal will convey sufficient information to make the speech sufficiently intelligible. This allows effective speech communication. However, a hearing impaired person has difficulty in detecting speech signals. This occurs because the speech signal is either inaudible or distorted. Subjects with sensory neural hearing loss (SNHL) need higher Signal to Noise Ratio (S/N) to reach the same speech understanding, compared to their counterpart's normal hearing subjects [1,2]. Although hearing aids improve the audibility of the speech signal, the background noise will be amplified together with speech. Accordingly, the signal to noise ratio (S/N) is not increased resulting in poorer speech intelligibility. This takes place due to the effect of increased upward spread of masking at high listening levels together with the distortion caused by the hearing aid [3].

Recent digital hearing aids enhance S/N by applying one of the noise reduction algorithms. Noise reduction algorithms aim to select speech and cancel noise depending on the acoustical parameters of speech versus noise. There are several digital techniques available for noise reduction including: spectral subtraction, harmonic extraction and analysis by synthesis [4]. Spectral subtraction is widely used to

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suppress additive noise in hearing aids. Noise spectrum is estimated during pauses in the incoming speech signal. Estimation takes place following the assumptions that noise magnitude spectrum does not change significantly. The next step is subtraction of the estimated noise values from speech to enhance speech intelligibility [5]. In modulation detection technique, classification of the signal as noise or speech is based on modulation detection. [6] reported that the modulation pattern of the syllables is approximately between 3 and 10 Hz. In contrast, environmental sounds tend to be more stable in terms of ongoing amplitude. Moreover, advanced microphone technology helps in improving S/N. Directional microphone (DM) technology has been applied in the field of hearing aids aiming to improve the speech intelligibility in noisy environment. The mechanism of fixed array directional microphones in speech enhancement depends on cancellation of rear unwanted signals trying to produce zero sensitivity for sound coming from behind. This makes the head orientation play a very important role in selection of the enhanced signal [7,8]. On the other hand, adaptive array produce the maximum possible sensitivity for sounds coming from the front and less sensitivity for sounds coming from all other directions. Meanwhile, the directional characteristics vary from moment to moment in order to adapt for the environment in such a way to minimize the pick-up of noise coming from particular directions [9]. Different studies were conducted to evaluate the role of noise reduction algorithm in improving speech intelligibility [10,5-11]. Other studies were conducted to evaluate the benefit from directional microphones [12-15]

As most of the available digital hearing aids are using one of noise reduction algorithms available. This study was conducted to evaluate the efficacy of combining directional microphone to noise reduction algorithm in improving speech intelligibility

Materials and Methods

Participants

The participant were 20 adults who ranged in age from 20 to 60 years (M= 42.8Ys). They had documented bilateral symmetrical moderate to moderately-severe sensori-neural hearing loss. They were first time hearing aid users. The participants had worn only one hearing aid (Oticon Tego pro power BTE Behind The Ear) at the time of participation in the study.

Hearing aid

Digital hearing aid, Oticon model Tego pro (BTE) power, has noise reduction algorithm option and adaptive directional microphone option with the ability to cancel one or both options. It was programmed through NOAH system: software SONIC innovations system and hearing instrument programmer (HI-PRO) with special cable according to patients' audiogram. It was fitted monoaurally according to the subject preference using NAL NL1 prescriptive formula.

Procedure

All participants in this study were tested in two assessment sessions. First session include: full history taking, otological examination, basic audiological evaluation. Pure-tone air-conduction thresholds were obtained for the frequencies of 250, 500, 1.000, 2.000, 4.000 and 8.000 Hz and bone-conduction thresholds for frequencies 500, 1.000, 2.000 and 4.000 Hz using a GSI, model 61 audiometer calibrated according to ANSI (1969)[16] and equipped with a sound field connection. Speech reception thresholds (SRT) using Arabic Spondee Word lists were assessed [17]. Word discrimination scores (DS) were obtained using Arabic Phonetically Balanced Words [18]. Figure 1 shows: the design of the used sound treated room. The participants were instructed to have ear impression before the second session.

Second session consisted of: assessment of the subject in unaided condition then his assessment in aided condition. Unaided assessment included: unaided sound field threshold determination using warble tones (the stimulus came from the loudspeaker at 0-degree azimuth), unaided Arabic Speech in noise Test (SPIN) was done using Arabic Phonetically Balanced (PB) words recorded in a back ground of cafeteria noise [19]. The stimulus was at most comfortable level with the maximum of 85 dBHL and S/N adjusted at 0 dB.

Unaided Just-Follow-Conversation Test (JFCT) [20] was done using the passages of Arabic speech intelligibility rating test (SIR) test monitored live voice from one loudspeaker at 0-degree azimuth and different types of noise (cafeteria, traffic and lecture) delivered from the other loudspeaker. For all unaided speech tests, the speech signal came from a loudspeaker one meter away at 0-degree azimuth and the noise signals came from a loudspeaker one meter behind at 180-degree azimuth. The previous described position was called position (A).

Aided assessment consisted of two types of aided assessment depending on the hearing aid setting. First aided setting was done using the noise reduction algorithm in the digital hearing aid with its omnidirectional microphone. The following steps were done: aided sound field thresholds determination using warble tones at frequencies 250, 500, 1000, 2000, 3000 and 4000 Hz (0-degree azimuth). Aided discrimination score (DS). Aided SPIN test at most comfortable level (aided SRT+ 40dB) with S/N adjusted at 0 dB and aided JFCT in position (A). Aided SPIN test was done in different positions include, position (A): speech came from loudspeaker at 0-degree azimuth and noise came from loudspeaker at 180-degree azimuth, position (B): speech came from loudspeaker at 90-degree azimuth and noise came from loudspeaker at 180-degree azimuth. Position (C): speech and noise were at 0-degree azimuth

Second aided setting was done using both noise reduction algorithm and adaptive directional microphone. The same aided assessment steps used in the first setting were reassessed with the second setting. Lastly, the subjective impression was obtained using a modified questionnaire for hearing aid assessment [7], after translation to Arabic, it was assessed and adapted to Egyptian culture. Each patient signed a consent showing the acceptance about the procedure and the aim of the research.

Results

Sound audibility

Sound audibility remains one of the most important parameters during assessment of accurate hearing aid fitting. In the current work, aided warble tones with noise reduction algorithm alone (first setting) as well as combined with directional microphone (second setting) gave better hearing thresholds compared to unaided results (Figure 1). This difference was statistically significant at 250-4000 Hz frequencies. Moreover, the mean aided thresholds for all patients, at all frequencies, lied within the average conversational levels of speech. This ensured the audibility of speech which is an important step needed before testing speech discrimination abilities in quiet and in noise.

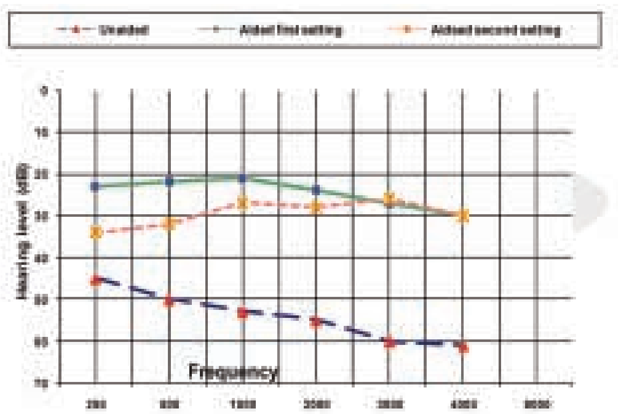

Figure 1. Unaided threshold versus aided thresholds using first setting and second setting. The unaided threshold (Δ), the aided threshold first setting (•), and the aided threshold second setting (x). This figure shows that both aided thresholds lie within the LTASS however, there is a difference between both aided responses at low frequency range (250-2000 Hz).

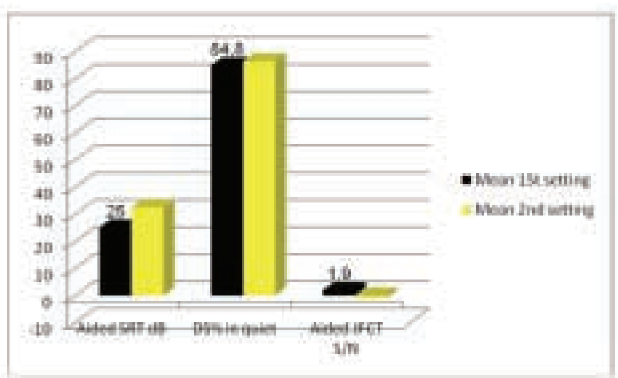

Figure 2. Aided speech reception threshold (SRT), Discrimination score (DS) & Just follow conversation test (JFCT) results in two different hearing aid settings.

In the current work, the noise reduction algorithm alone (first setting) gave better gain compared to noise reduction with directional microphone (second setting) in the frequency range between 250-2000 Hz. This difference was statistically significant.

Speech test results

At thresholds, speech reception abilities were evaluated. Both first setting and second setting showed a statistical improvement compared to unaided SRT (Tables 1-3). The first setting showed better SRT than second setting (Table 4, Figure 2).

Table 1. Mean, standard error (SE) and range of unaided speech tests.

Variable		Mean ± S.E.	Range
Unaided SRT	dB	52.3±0.1	45-70
Unaided DS	%	82.1±1	52-92
Unaided SPIN	%	60.8±3.4	32-76
Unaided JFCT	dB	2.9±0.96	-4-8

At suprathresholds, Speech discrimination scores in quiet showed no statistical significant difference between aided and unaided results (Tables 1-3). Additionally, no statistical significant difference between speech discrimination scores in quiet in both aided settings was noted (Table 4, Figure 2).

In position (A) “speech at 0-degree azimuth/ noise at 180-degree azimuth”, no statistical significant difference detected between unaided results and aided first setting (Table 2). On the other hand, there was a statistical significant improvement in SPIN test results in second setting compared to first setting and unaided setting (Tables 3, 4, Figure 3).

As the position of speaker may change in real-life situations, SPIN test was conducted in position (B) “speech at 90-degree azimuth/ noise at 180-degree azimuth”, no statistical significant difference was detected between both aided settings (Table 4, Figure 3).

Meanwhile, in position (C) when speech and noise were at zero-degree azimuth, the directional microphone with noise reduction algorithm (second setting) gave better SPIN test results compared to first setting (Table 4).

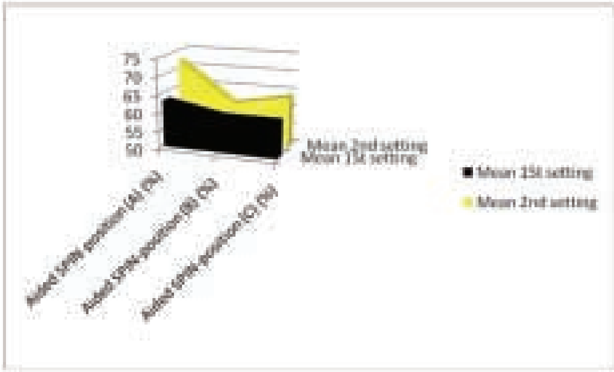

Figure 3. Comparison between aided speech in noise tests in (first setting) versus aided speech in noise tests (second setting) in the three different noise scenarios, positions A,B and C.

Changes in SNR ratio

Improvement in S/N was detected by JFCT in both aided settings in relation to unaided condition (Table 1-3). However, directional microphone with noise reduction algorithm (second setting) showed less S/N than first setting (Table 4).

Effect of variance:

In the current work, the effect of different variance on directional benefit was addressed using SPIN and JFCT. Better SPIN scores were achieved in the moderate than the moderately-severe sensorineural hearing loss subjects. This difference was statistically significant in both aided settings (Table 5). The benefit from directional microphone was elicited in position (A&C) relative to noise reduction algorithm setting (Table 5) whatever the degree of hearing loss.

Studying the effect of duration of hearing loss showed that subjects with hearing loss duration less than 10-years gave better SPIN scores with less S/N (using JFCT) than those suffering from hearing loss for more than 10-years. This difference in performance was statistically significant (Table 6). It should be emphasized that the directional benefit was preserved in position (A&C) whatever the hearing loss was less or more than 10 years.

In the present study, the modified questionnaire was used to evaluate the subjective directional impression in different types of noise. This modified questionnaire for hearing aid assessment focused on proper fitting, ease of communication and effect of background noise.

Subjectively, all patients reported the ability of directional hearing aid to give better speech quality. Meanwhile, analysis of the questionnaire after using directional microphone showed that 50% of patients had moderate ability to discriminate in background noise while the other 50% reported excellent ability to discriminate in background noise. All patients could not feel changes by different types of noise used (traffic, cafeteria and lecture noise).

Discussion

Sound audibility:

Expectedly, in the current work, the noise reduction algorithm alone (first setting) gave better gain compared to noise reduction with directional microphone (second setting) in the frequency range between 250-2000 Hz. This difference was statistically significant. This could be attributed to the fact that DMs are less sensitive in low frequencies than their omnidirectional counterparts for sounds at zero-degree azimuth [14, 12-19]. Low frequencies have long wave length, when DM samples low frequencies, this makes each two points sampled having higher opportunity to be of the same phase as the two ports are very near to each other. In the contrary, during sampling high frequency sounds, there is a higher opportunity to sample two different phases due to shorter wave length. Subsequently, after phase cancellation, a relative reduction in output for low frequencies will occur with DMs.

Speech test results

Both first setting and second setting showed a statistical improvement compared to unaided SRT (Tables 1, 2 and 3). However, the first setting showed better SRT than second setting (Table 4 and Figure 1). This could be interpreted on the basis that SRT depends mainly on hearing thresholds at 250 and 500Hz [20] which were less amplified when DM was used.

At suprathresholds, speech discrimination is fundamental to the communication process. Speech discrimination scores in quiet showed no statistical significant difference between aided and unaided results (Tables 1-3). This was expected as word discrimination scores were tested at the most comfortable level. However, Reber and Kampis [21] reported the substantial increase in speech intelligibility without significant changes of the insertion gain of the hearing aid over 6-months of regular use. Additionally, no statistical significant difference between speech discrimination scores in quiet in both aided settings was noted (Table 4, Figure 2). Frank and Gooden [22] clarified that benefits acquired from directionality is not expected to be present in quiet, non reverberant listening situations. Moreover, Lee et al. [23] demonstrated that, in comparison to an omnidirectional mode, a directional mode can reduce speech recognition in quiet only when the loudspeaker of interest is behind the listener.

SPIN testing in three different scenarios was done as the ultimate aim of the study was to measure the ability to perceive speech information in such a way that reflects the real-world performance. SPIN scores (Table 4, Figure 3) showed that: In position (A) “speech at 0-degree azimuth/ noise at 180-degree azimuth”, no statistical significant difference detected between unaided results and aided first setting (Table 2). Ricketts[11] used different digital hearing aids with different noise reduction algorithms. They demonstrated that after regular use of hearing aids, there was no significant effect on speech in noise test results. In the present study, although patients were first hearing aid users, yet the same finding was reported when noise reduction algorithm only was used. However, Kuk et al. [24] showed improvement in speech understanding after 6-month use of hearing aid with noise reduction and omnidirectional microphone in auditory processing disorder children. On the other hand, there was a statistical significant improvement in SPIN test results in second setting compared to first setting and unaided setting (Table 3, 4, Figure 3). The superiority of directional microphone combined with noise reduction algorithm (second setting) in improving SPIN test scores is attributed to cancellation of noise coming from behind which is performed by the DM.

As the position of speaker may change in real-life situations, SPIN test was conducted in position (B) "speech at 90-degree azimuth/ noise at 180-degree azimuth", no statistical significant difference was detected between both aided settings (Table 4, Figure 3).This was not expected as the directional microphone used in this study was a fully adaptive one which should have the ability to adapt according to speech source. This means that the adaptive circuit in adaptive DM may not be efficient in adaptation to changes in the tested noise scenario. This is especially because; our sound source was fixed at 90 -degree azimuth and not changing from moment to moment as supposed to initiate the adaptive circuit. However, Ricketts [25] reported such result only when a fixed directional microphone was used.

Meanwhile, in position (C) when speech and noise were at zero-degree azimuth, the directional microphone with noise reduction algorithm (second setting) gave better SPIN test results compared to first setting (Table 4). This result was not expected as, in this position (C) (speech-front/ noise-front), the noise reduction system should mainly depend on acoustic parameters of speech versus noise. Nevertheless, this could be attributed to the fact that directional microphones have low sensitivity to low frequency sounds that mask the meaningful high frequency consonant sounds. Moore [26] assumed that, reduction of low frequency gain minimizes the upward spread of masking phenomenon and helps in making all bands of speech equally loud. On the contrary, Kevin et al. [27] reported no statistically significant difference between noise reduction algorithm alone and combined with directional microphone in a noise scenario similar to position (c) in the current work. They used different speech material (sentences) and different noise spectrum (speech weighted noise).The directional microphone seems to be of low sensitivity to low frequency sounds and not to speech frequency that was used as background noise in Kevin's study.

Changes in SNR ratio

The importance of maintaining signal level well above those of competing noise is well recognized and had been studied in many research works [19, 28]. In the current work, Just-follow-conversation test (Table 4, Figure 2) was used to evaluate the least S/N a subject can tolerate with his best concentration, to follow conversation. Improvement in S/N was detected by JFCT in both aided settings in relation to unaided condition (Table 1-3). However, directional microphone with noise reduction algorithm (second setting) showed less S/N than first setting (Table 4) indicating superiority of addition of the DM in enabling the hearing aid user to follow a conversation in a very noisy environment. This is due to the ability of directional microphone to cancel noise coming from behind.

Effect of variance:

Table 2. Comparison between unaided speech tests versus aided speech tests (first setting) using Duncan's Multiple Range Test.

Variable		Unaided sound field Mean±SE	Range in dBHL	Aided first setting Mean±SE	Range in dBHL	P-value
Average SRT	dB	52.8±1.7	40-70	25±1.4	20-35	>0.01**
DS in quiet	%	82.1±1	52-92	84.8±1.9	56-92	<0.05
SPIN at position (A)	%	59.7±3.8	32-76	61.5±3.8	40-80	<0.05
JFCT	dB	2.8±1.2	-4-8	1.7±1.2	-6-8	>0.05*

Table 3. Comparison between unaided speech tests versus aided speech tests (second setting) using Duncan's Multiple Range Test.

Variable		Unaided sound field Mean± SE	Range	Aided second setting Mean±SE	Range	P-value
Average SRT	dB	52.8±1.3	40-70	33.2±1.3	25-40	>0.01**
DS in quiet	%	82.1±1	52-92	86.4±1.8	60-100	<0.05
SPIN at position (A)	%	59.5±3.1	32-76	70.7±3.1	44-88	>0.01**
JFCT	dB	2.9±1.2	-4-8	-1.1±1.2	-8-6	>0.01**

Table 4. Comparison between aided speech tests (first setting) versus aided speech tests (second setting) using Duncan's Multiple Range Test:

Variable	Aided first setting Mean± SE	Range	Aided second setting Mean±SE	Range	P-value
Aided SRT dB	25±1.4	20-35	33.8±1.3	25-40	>0.01**
DS% in quiet	84.8±1.9	56-92	86.4±1.4	60-100	<0.05
SPIN position (A) %	60.3±3.2	40-80	69.7±3.2	44-88	>0.01**
SPIN position (B) %	59.8±2.8	36-72	59.9±3.1	32-76	<0.05
SPIN position (C) %	57.9±2.7	32-76	61.38±2.7	44-88	>0.05*
JFCT in dB	1.6±1.3	-6-8	-1.1±1.3	-8-6	>0.01**

Table 5. Effect of degree of hearing loss on directional benefit and SPIN test results (in the two aided settings at different loudspeakers positions).

Variables	Degree of hearing loss	
	Moderate	Moderatly-severe
Aided SPIN first setting position (A) %	68.4±3.5 a	41.9±3.4 b
Aided SPIN second setting position (A) %	73.4±2.8 a	59.2±4.3 b
P Value		
Directional benefit	<0.05	<0.05
Aided SPIN first setting position (B) %	61.4±2.9 a	45.7±4.5 b
Aided SPIN second setting position (B) %	62.9±3.1 a	44.3±4.8 b
P value		
Directional benefit	>0.05	>0.05
Aided SPIN first setting position (C) %	63.1±2.8 a	41.9±4.3 b
Aided SPIN second setting position (C) %	65.6±2.9 a	47.5±3.9 b
P Value		
Directional benefit	<0.05	<0.05

Table 6. Effect of duration of hearing loss on directional benefit and SPIN test results in the two aided settings with different loudspeakers positions:

Variables	Duration of hearing loss		
	1->5 years	5->10 years	More than 10years
Aided SPIN first setting position (A) %	69.6±5.1 a	64.8±9.5 a	40.4±8.4 b
Aided SPIN second setting position (A) %	74.4±3.2 a	77.5±6.1 a	54.8±5.4 b
P value			
Directional benefit	<0.05	<0.05	<0.05
Aided SPIN first setting position (B) %	60.8±4.1 a	62.2±7.6 a	45.9±6.8 b
Aided SPIN second setting position (B) %	61.5±5 a	62.9±7.6 a	44.6±8.4 b
P value			
Directional benefit	>0.05	>0.05	>0.05
Aided SPIN first setting position (C) %	64.8±3.8 a	60.7±7.1 a	39.1±6.3 b
Aided SPIN second setting position (C) %	66.8±4.1 a	64.1±9.4 a	49.7±6.8 b
P value			
Directional benefit	<0.05	<0.05	<0.05

In the current work, the benefit from directional microphone was elicited in position (A&C) relative to noise reduction algorithm setting (Table 5) whatever the degree of hearing loss. It should be emphasized that the directional benefit was preserved in position (A&C) whatever the hearing loss was less or more than 10 years.

Subjects with hearing loss duration less than 10-years gave better SPIN scores with less S/N (using JFCT) than those suffering from hearing loss for more than 10-years. This difference in performance was statistically significant (Table 6). This could be attributed to more deterioration in the degree of hearing loss in the group exceeding 10-years of hearing loss or to the long-standing auditory deprivation that lead to central auditory changes affecting speech perception performance [29, 30]. It should be emphasized that the directional benefit was preserved in position (A&C) whatever the hearing loss was less or more than 10 years.

Unexpectedly, at position (B) in our study where the speech was at 90-degree azimuth the adaptive directionality failed to gain any extra benefit than first setting (omnidirectional microphone + noise reduction algorithm). This means that adaptive directional microphone will fail to give convenient speech intelligibility if the subject is moving in all directions. As children are moving all the time, we need an extra work to assess the benefit from adaptive directional microphone in younger age group than those enrolled in this study. As a matter of fact the Pediatric Working Group [31] reported limited benefit from directional microphone in preschool children.

Satisfaction with a hearing aid is a complex subjective phenomenon that is affected by a variety of auditory as well as non-auditory factors. Newman and Sandridge[32] recommended the use of the self assessment questionnaires that represent an indirect measure of the individual's performance Subjectively, in the present study all patients reported the ability of directional hearing aid to give better speech quality. This result is supported by a previous research work conducted by Ricketts [14] who demonstrated subjective preference to directional microphone.

In conclusion, the results of the current work confirmed the ability of noise reduction algorithm and directional microphone in improving the S/N with preference to directional microphone when combined with noise reduction algorithm. It highlighted, as well, the superiority of the directional microphone in enhancement of speech intelligibility in noisy situations when speech was at zero-degree azimuth and the noise was at zero or 180-degree azimuth. However, the benefit achieved from the adaptive directional option in the hearing aid used was limited when speech was at 90-degree azimuth; this point will need to be fully addressed in a future work. The results of the present study should be documented by prolonged use which could not be achieved in this study. Moreover, the benefit from directional microphone for school children should be addressed in a future work.

Acknowledgement

The authors are very grateful to all the participants from Ain Shams University Hospital for their help in this study. We really appreciate the help of the international and the local (El-Neil Llmashroat) Oticon group for supplying the hearing aid and for their technical support throughout this work.

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