



## Original Article

# Efficacy of Directional Microphones in Hearing Aids Equipped with Wireless Synchronization Technology

Chinnaraj Geetha, Kishore Tanniru, R. Raja Rajan

Department of Audiology, All India Institute of Speech and Hearing, Mysore, Karnataka, India

**OBJECTIVE:** This study aimed to evaluate the use of directionality in hearing aids with wireless synchronization on localization and speech intelligibility in noise.

**MATERIALS and METHODS:** This study included 25 individuals with bilateral mild to moderate flat sensorineural hearing loss. For the localization experiment, eight loudspeakers (Genelec 8020B) arranged in a circle covering a 0–360° angle and the Cubase 6 software were used for presenting the stimulus. A car horn of 260 ms was presented from these loudspeakers, one at a time, randomly. The listener was instructed to point to the direction of the source. The degree of the localization error was obtained with and without directionality and wireless synchronization options. For speech perception in a noise experiment, signal to noise ratio-50 (SNR-50) was obtained using sentences played through a speaker at a fixed angle of 0°. A calibrated eight-talker speech babble was used as noise and the babble was routed either through 0°, 90°, 270° (through one speaker at a time) or through both 90° and 270° speakers.

**RESULTS:** The results revealed that the conditions where both the wireless synchronization and directionality were activated resulted in a significantly better performance in both localization and speech perception in noise tasks.

**CONCLUSION:** It can be concluded that the directionality in the wireless synchronization hearing aids coordinates with each other binaurally for better preservation of binaural cues, thus reducing the localization errors and improving speech perception in noise. The results of this study could be used to counsel and justify the selection of the directional wireless synchronization hearing aids.

**KEYWORDS:** Wireless synchronization, localization, speech perception, SNR-50, directionality

## INTRODUCTION

Speech in noisy backgrounds is a challenging situation for listeners with sensorineural hearing loss. Cues that are responsible for better understanding speech in noise are interaural time differences (ITD) and interaural level differences (ILD) along with other binaural cues in individuals with normal hearing<sup>[1]</sup>. Hence, preservation of binaural cues is said to be crucial for localization as well as speech understanding<sup>[2]</sup>. The same applies to even the hearing aid users if they are using binaural amplification.

Directional microphones in hearing aids are designed to provide attenuation to the sounds, which are emerging from the sides of the listener and are concentrated only in front of the listener<sup>[3]</sup>. Directionality also plays a main role in understanding speech in noise because it maintains the interaural cues. They are reported to result in improved speech recognition when speech and noise are coming from different directions<sup>[4]</sup>.

However, it has been reported that directionality in binaural hearing aids without wireless communication disrupt the cues for localization, that is, ITD and ILD cues. This leads to poor performance in localization as well as in speech perception in noise<sup>[5,6]</sup>. Hence, there was a need for technology that can facilitate one to one communication between hearing aids which helps to preserve these ILD and ITD cues. This led to the invention of hearing aids with ear to ear synchronization facilities. Ear to ear synchronization or wireless synchronization technology is a modern technology added to some of the current digital hearing aids. These hearing aids communicate with each other and give binaural information to the brain<sup>[7]</sup>.

Kreisman et al.<sup>[7]</sup> studied speech perception in noise in 36 listeners with sensorineural hearing loss with binaural hearing aids with and without wireless synchronization in two different models of hearing aids. All the digital signal processing algorithms were activated in the study. They assessed speech perception using QuickSIN and Hearing in Noise Test (HINT). For the QuickSIN test, the speech babble was presented through the loudspeakers at +135° and –135° azimuth in the first condition and given from the loudspeakers at ±45° and ±135° azimuth in the second condition. The results showed a significant improvement in performance

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**Corresponding Address:** Chinnaraj Geetha E-mail: geethamysore.cs@gmail.com

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on both the tests with the hearing aids with wireless synchronization when compared to hearing aids without it. They also reported that the newer model of hearing aid yielded better results when compared to the older one.

A study done by İbrahim et al.<sup>[8]</sup> assessed the localization ability along with speech intelligibility of listeners with hearing impairment using different brands of bilateral wirelessly connected wide dynamic range compression (WDRC) hearing aids. Twenty listeners participated in their study out of which twelve had moderate to severe hearing impairment and eight had normal hearing. All listeners were tested with HINT and measured for errors in localization in both the Front/Back and Left/Right dimensions as a part of the localization experiment with and without wireless synchronization. They had deactivated all other digital signal processing (DSP) algorithms unlike Kreisman et al.<sup>[7]</sup> study. They reported that wireless synchronization significantly improved Front/Back localization in individuals with hearing loss. However, İbrahim et al.<sup>[8]</sup> showed no significant change in the HINT scores with wireless synchronization. The differences in the results between the above two studies have been attributed to the differences in the method. Kreisman et al.<sup>[7]</sup> had conducted experiments with all DSP features activated, whereas İbrahim et al.<sup>[8]</sup> had deactivated all advance DSP features. This could have led to no specific benefit from wireless WDRC synchronization in İbrahim et al.<sup>[8]</sup> study.

Sockalingam et al.<sup>[9]</sup> also assessed the sound quality and localization ability of 30 listeners fitted with hearing aids with and without wireless synchronization. The results showed that in the "wireless on" condition, the listeners obtained significantly lesser localization errors in the presence of noise than in the "wireless off" condition. However, the authors have not mentioned whether DSP algorithms such as digital noise reduction algorithm (DNR) and directionality were activated. Hence, the results of this study do not facilitate in completely understanding the working of wireless hearing aids.

To summarize, the above studies have adopted different measures of performance of wireless hearing aids (e.g., Kreisman et al.<sup>[7]</sup> studied only speech perception, whereas Sockalingam et al.<sup>[9]</sup> assessed sound quality and localization ability) using different methodology leading to equivocal results. In addition, some studies have evaluated the effect of only the wireless WRDC synchronization on speech perception in noise<sup>[8]</sup> while some have studied the effect of wireless synchronization with all the DSP features (directionality and DNR) activated together<sup>[7]</sup> or there is no mention of directionality being activated or deactivated<sup>[9]</sup>. To our knowledge, there are no published reports evaluating the directionality in the WDRC binaural wireless hearing aids in comparison with the non-wireless hearing aids. It is important to systematically evaluate the directionality with the wireless hearing aids to provide scientific evidence. This will help in justifying the selection of the wireless hearing aids and in counseling the listeners while making decisions about the selection of hearing aids. Hence, the present study aimed to evaluate the use of directionality in hearing aids with wireless synchronization technology on localization abilities and speech intelligibility in noise. The objectives of this study were to assess localization and speech intelligibility in noise with and without directionality and wireless options in individuals with hearing impairment with binaural WDRC hearing aids.

## MATERIALS and METHODS

This study included 25 participants with bilateral mild to moderate flat sensorineural hearing loss. They were naive hearing aid users in the age range of 18–55 years (males=13, females=7) with a mean age of 39 years. Participants who had middle ear pathology and neurological and psychological problems were excluded from the study. A calibrated dual-channel diagnostic audiometer was used for obtaining the pure tone thresholds, speech recognition threshold, and speech identification scores. The audiometer was connected to the TDH 39 headphones, Radio Ear B-71 Bone vibrator, and two loudspeakers located at a 45° angle for routine evaluation. Tympanometry and acoustic reflex assessment had been carried out with a GSI-Tympstar middle ear analyzer to check the functioning of the middle ear.

Two digital WDRC hearing aids of the same model with the facility of wireless transmission; with the fitting range of mild to moderately severe degree of hearing loss; with directionality microphone option; and with the option of disabling/enabling the above features individually will be used. A computer with an Intel Core 2 Duo processor with Windows 7 configuration was used to program the hearing aids. Programming was done through the NOAH link with appropriate cables and software. Two hearing aids with wireless technology were programmed and fitted using routine hearing aid evaluation procedures. The study got ethical clearance before starting the data collection. Informed written consent was taken from all the participants of the study.

### Localization Experiment

Eight Genelec 8020B loudspeakers (Thomann GmbH, Burgebrach, Germany) mounted on an Iso-Pod™ (Isolation position/decoupler™) vibration insulating stand located at 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315° azimuth were used for the localization experiment. These eight loudspeakers (Genelec 8020B) were arranged in a circle covering 0°–360° angles. Cubase 6 software was used for presenting the signal for the localization experiment. A car horn of 260 ms was sounded as target stimuli. The stimulus was calibrated and presented at 70 dB SPL. Bruel and Kjaer handheld analyzer (model no. 2270) sound level meter (Bruel and Kjaer, Nærum, Denmark) was used with a half inch free-field microphone for the calibration of the stimuli.

The stimulus was given from the loudspeakers kept at a 1 feet distance, one after the other, randomly. The participants were instructed to point to the direction of the source. The clinician noted down the response of the participant in a response sheet designed for this test. From each loudspeaker, the target stimuli were presented thrice randomly for each condition and an average of the three responses was calculated. Hence, there were 24 trials in each condition. Then, the degree of error (DOE) was calculated for each loudspeaker. The degree of error corresponded to the difference in degrees between the azimuth of the loudspeaker of the actual presentation of the stimuli and the azimuth of the loudspeaker identified as the source of the stimulus by the participant. Using the degree of error for each speaker, the root mean square degree of error (rmsDOE) for each condition was calculated. The formula for calculating rmsDOE was as follows:

$$rms\ DOE = \frac{\sqrt{(DOE)^1^2 + (DOE)^2^2 + \dots + (DOE)^8^2}}{8}$$

### Speech Perception in Noise Experiment

Participants were seated in the same setup as the previous experiment. Speech intelligibility in noise was assessed using the sentence

test in Kannada language developed by Geetha et al. [10]. This test has 25 equivalent lists with ten sentences each. Calibration was done using the above used procedure. The sentences in Kannada language were presented in a) quiet situation, b) speech babble from the front (0° angle), c) speech babble from the right (90° angle), d) speech babble from the left (270° angle), and e) speech babble from both 90° angles and 270° angle speakers. In all conditions, the sentence list was presented from a 0° angle. Kannada speech babble was used as noise. The speech babble was presented at a constant noise level of 70 dB SPL, and the intensity of the speech stimuli was varied to find out signal to noise ratio-50 (SNR-50). The listeners repeated the words in each sentence. The tester varied the level of sentences till the person repeated 50% of the keywords in the sentence. The difference in the level of noise and speech was noted down as SNR-50.

Before the actual test began, a practice session was conducted. Test conditions were randomized and counterbalanced to reduce order effects. Each sentence list was used only once to avoid the practice effect. The listeners were not aware of the conditions under which the testing was being done.

**Table 1.** Mean and SD of rmsDOE in different aided conditions (n=25)

rmsDOE	Mean	SD
Wireless on directionality on	27.9	6.2
Wireless on directionality off	31.4	6.4
Wireless off directionality on	31.8	5.9
Wireless off directionality off	36.9	6.0

Wireless on: wireless synchronization enabled; Wireless off: wireless synchronization disabled; Directionality on: directionality algorithm enabled; Directionality off: directionality algorithm disabled; rmsDOE: root mean square Degree of Error; SD: standard deviation

**Table 2.** Pairwise comparison of rmsDOE across different aided conditions (n=25)

Conditions	Compared condition	Mean difference (I-J)
Wireless on directionality on	Wireless on directionality off	-3.4**
	Wireless off directionality on	-3.9**
	Wireless off directionality off	-9.0**
Wireless off directionality off	Wireless on directionality on	9.0**
	Wireless on directionality off	5.5**
	Wireless off directionality on	5.0**

Only the significant effects are given; \*\*p<0.01; Wireless on: wireless synchronization enabled; Wireless off: wireless synchronization disabled; Directionality on: directionality algorithm enabled; Directionality off: directionality algorithm disabled.

**Table 3.** Mean and SD of SNR-50 in all aided conditions (n=25)

Speaker Azimuth Conditions	0°		90°		270°		90° & 270°	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Wireless on directionality on	4.0	1.0	3.3	0.9	3.9	0.7	5.2	0.9
Wireless on directionality off	4.9	1.0	4.3	0.7	4.5	0.9	6.4	0.8
Wireless off directionality on	5.0	1.0	4.7	0.9	4.9	1.0	6.0	0.8
Wireless off directionality off	5.4	1.0	6.1	0.5	6.3	0.7	7.6	0.8

Wireless on: wireless synchronization enabled; Wireless off: wireless synchronization disabled; Directionality on: directionality algorithm enabled; Directionality off: directionality algorithm disabled; SD: standard deviation

## RESULTS

### Localization Experiment

The mean and standard deviation (SD) of rmsDOE is given in Table 1. From Table 1, it can be seen that mean value for rmsDOE ranged from 27.9° to 36.9°. Lesser rmsDOE indicates a better localization ability.

It can also be observed that the localization errors were lesser when both wireless synchronization and directionality were enabled compared to the conditions where either only one of it was enabled or both were disabled. To see if these differences were statistically different, repeated measures ANOVA was carried out. The results showed a significant difference (F (2.204, 52.9)=61.9, p<0.001). Hence, Bonferroni pairwise comparison was done among the conditions. The results of the Bonferroni pairwise comparison are given in Table 2.

The conditions where wireless synchronization was enabled along with directionality had significantly better performance compared to all other conditions (Table 2). It can also be noted that there was a statistically significant difference (p<0.01) found for conditions where wireless synchronization was on compared to conditions where it was off. In addition, the presence of directionality without wireless synchronization did not bring about good localization. Hence, it can be stated that the presence of wireless synchronization enhanced the performance of the directional microphones.

### Speech Intelligibility Experiment

The mean and SD of SNR-50 in all eight conditions are given in Table 3. SNR-50 obtained with different conditions was subjected to statistical analysis using the SPSS software version 20.

From Table 3, it can be observed that the mean SNR-50 value ranged from +4.0 dB to +7.6 dB overall. A lesser SNR-50 value indicates better performance and a larger SNR-50 indicates poorer performance. Friedman’s test was done for SNR-50 in all azimuths. There was a significant effect observed ( $\chi^2(15)=240.02$ ) at p<0.01 level of significance. To find out which of the conditions differed from each other, Wilcoxon signed-rank test was conducted. The results of the test are given in Table 4.

As shown in Table 4 that when the speech babble and the speech were given from the same direction (0°), only the algorithms where directionality and wireless synchronization were enabled were significantly (p<0.05) better than all other conditions.

From Table 5, 6, and 7, it can be observed that the results comparing SNR-50 in different azimuth were similar to that obtained in the local-

**Table 4.** Pairwise comparison of SNR-50 at 0° azimuth

Conditions	Wireless on directionality on	Wireless on directionality off	Wireless off directionality on	Wireless off directionality off
Wireless on directionality on	--	0.001***	0.002**	0.000***
Wireless on directionality off	0.001***	--	0.819	0.134
Wireless off directionality on	0.009	0.819	--	0.197
Wireless off directionality off	0.000***	0.134	0.197	--

Significant effects are in bold; \*\*p<0.01; \*\*\*p<0.001; Wireless on: wireless synchronization enabled; Wireless off: wireless synchronization disabled; Directionality on: directionality algorithm enabled; Directionality off: directionality algorithm disabled.

**Table 5.** Pairwise comparison of SNR-50 at 90° azimuth

Conditions	Wireless on directionality on	Wireless on directionality off	Wireless off directionality on	Wireless off directionality off
Wireless on directionality on	--	0.001***	0.000***	0.000***
Wireless on directionality off	0.001***	--	0.025	0.000***
Wireless off directionality on	0.000***	0.025	--	0.000***
Wireless off directionality off	0.000***	0.000***	0.000***	--

Significant effects are in bold; \*\*\*p<0.001; Wireless on: wireless synchronization enabled; Wireless off: wireless synchronization disabled; Directionality on: directionality algorithm enabled; Directionality off: directionality algorithm disabled.

**Table 6.** Pairwise comparison of SNR-50 at 270 azimuth

Conditions	Wireless on directionality on	Wireless on directionality off	Wireless off directionality on	Wireless off directionality off
Wireless on directionality on	--	0.005**	0.000***	0.000***
Wireless on directionality off	0.005**	--	0.025	0.000***
Wireless off directionality on	0.000***	0.025	--	0.000***
Wireless off directionality off	0.000***	0.000***	0.000***	--

Significant effects are in bold; \*\*p<0.01; \*\*\*p<0.001; Wireless on: wireless synchronization enabled; Wireless off: wireless synchronization disabled; Directionality on: directionality algorithm enabled; Directionality off: directionality algorithm disabled.

**Table 7.** Pairwise comparison of SNR-50 at 90 & 270 azimuth

Conditions	Wireless on directionality on	Wireless on directionality off	Wireless off directionality on	Wireless off directionality off
Wireless on directionality on	--	0.000**	0.003*	0.000**
Wireless on directionality off	0.000**	--	0.025	0.000**
Wireless off directionality on	0.003*	0.025	--	0.000**
Wireless off directionality off	0.000**	0.000**	0.000**	--

Significant effects are in bold; \*\*p<0.01; \*\*\*p<0.001; Wireless on: wireless synchronization enabled; Wireless off: wireless synchronization disabled; Directionality on: directionality algorithm enabled; Directionality off: directionality algorithm disabled.

ization experiment in both 90° and 270° azimuth conditions. That is, the conditions where both wireless synchronization and directionality were enabled had significantly better performance compared to all other conditions (p<0.01). It can also be noted that there was a statistically significant difference (p<0.01) found between the conditions where wireless synchronization was enabled compared to conditions where synchronization was disabled. In addition, the presence of directionality without wireless synchronization did not bring about good localization.

**DISCUSSION**

**Use of Directionality on Localization in Hearing Aids with Wireless Synchronization**

From the results, it can be noted that directionality in hearing aids with wireless synchronization technology helped for better localization. The condition where only directionality was activated resulted

in a mean error of 31.8°, but directionality along with the wireless synchronization technology yielded better localization accuracy where the mean error was 27.9°. Activation of both wireless synchronization and directionality together resulted in a significant improvement of 4° in the localization ability. These findings of the current study are consistent with the results of Van den Bogaert et al. [11]. They reported that persons with hearing impairment found it difficult to localize accurately even after the fitting of bilateral hearing aids without synchronization. They also stated that these hearing aids tend to distort the binaural cues which are much important for horizontal localization because the signals are processed separately in both the hearing aids. Further, from the results of the present study, it can be stated that activation of wireless synchronization has helped the microphones coordinate and preserve binaural cues better compared to the hearing aid without this facility, thus improving horizontal plane localization skill in persons with hearing impairment.



From the results of the present study, it could also be observed that the wireless technology alone improved horizontal plane localization skills significantly in persons with hearing impairment. This is evident from significant differences between the conditions “Wireless On Directionality Off” and “Wireless Off Directionality Off.” These results are consistent with the results of the study done by Ibrahim et al. [8].

Sockalingam et al. [9] also found that individuals with hearing impairment performed well in localization tasks when synchronization was on compared to the condition where synchronization was off. They had reported an improvement of 14% in the localization performance when wireless synchronization was switched on. This indicates that hearing aids with wireless synchronization preserve the ITD and ILD cues better when compared to hearing aids without the synchronization facility. They reported that since there is an exchange of information between the left and right hearing aids, participants had access to the full range of binaural cues essential for localizing the sound source, thus indicating better performance in the localization ability.

### Use of Directionality on Speech Perception in Noise

The present study showed that the wireless synchronization significantly improved speech perception in noise when compared to the condition without wireless synchronization. Studies have also reported that since the hearing aids work independently in both ears, there is a lack of these spatial cues. They also have reported that speech perception ability might increase when there is a coordination or exchange of information between both ears [6,7]. Hence, binaural wireless synchronization technology did improve speech perception in noisy situations to some extent due to the preservation of binaural cues and especially spatial cues.

These results are in concurrence with Kreisman et al. [7] study, wherein they found a significantly higher performance with the wireless synchronization when tested with the QuickSIN and HINT tests. However, Kreisman et al. [7] reported that they did not find any significant difference in the QuickSIN test. The reason could be that in Ibrahim et al. [8] study, DNR and directionality algorithms had been deactivated in all test conditions and only the WDRC was on along with wireless transmission. They also reported that the participants included in their study were older population and age-related cognitive deficits may also have influenced their results.

Further, directionality also played a significant role in speech perception along with this wireless synchronization when speech and noise were presented from different directions. This could be because the directional microphone works on the basis of spatial separation between speech and noise [12], and in the present study, the spatial separation was present in three azimuth conditions.

### CONCLUSION

It can be concluded that wireless hearing aids do benefit the individuals with a mild to moderate degree of hearing loss in speech perception in noise and localization in the given stimulus conditions. It can also be concluded that there was a significant improvement in understanding speech in noise and accuracy of horizontal plane localization using the directional microphones in wireless synchronization hearing aids when compared to that without the wireless synchronization option. The results of this study could be used to

counsel and justify the selection of the directional wireless synchronization hearing aids.

**Ethics Committee Approval:** Ethics committee approval was received for this study from the All India Institute of Speech and Hearing ethical committee.

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

**Peer-review:** Externally peer-reviewed.

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### REFERENCES

1. Wightman, FL & Kistler, DJ. Factors affecting the relative salience of sound localization cues. In: Gilkey, RH & Anderson, TR., eds. Binaural and spatial hearing in real and virtual environments. Hillsdale, NJ: Lawrence Erlbaum Associates. 1997; 1-23.
2. Hawley ML, Litovsky RY, Colburn HS. Speech intelligibility and localization in a multi-source environment. *J. Acous Soc Am* 1999; 105: 3436-48. [\[CrossRef\]](#)
3. Kuk F, Keenan D, Lau CC, Ludvigsen C. Performance of a Fully Adaptive Directional Microphone to Signals Presented from Various Azimuths. *J Am Acad Audiol* 2006; 16: 333-47. [\[CrossRef\]](#)
4. Ricketts TA, Henry PP, Hornsby BW. Application of frequency importance functions to directivity for prediction of benefit in uniform fields. *Ear Hear* 2005; 26: 473-86. [\[CrossRef\]](#)
5. Dirks DD, Wilson RH. The effect of spatially separated sound sources on speech intelligibility. *J Speech Hear Res* 1969; 12: 5-38. [\[CrossRef\]](#)
6. Keidser G, Hamacher V, Carter L, Dillon H, Rass U, Rohrseitz K. The effect of multi-channel wide dynamic range compression, noise reduction, and the directional microphone on horizontal localization performance in hearing aid wearer. *Int J Audiol* 2006; 45: 563-79. [\[CrossRef\]](#)
7. Kreisman BM, Mazeveski AG, Schum DJ, Sockalingam R. Improvements in speech understanding with wireless binaural broadband digital hearing instruments in adults with sensorineural hearing loss. *Trends Ampli* 2010; 14: 3-11. [\[CrossRef\]](#)
8. Ibrahim I, Parsa V, Macpherson E, Cheesman M. Evaluation of speech intelligibility and sound localization abilities with hearing aids using binaural wireless technology. *Audiol Res* 2012; 3: e1. [\[CrossRef\]](#)
9. Sockalingam R, Eneroth K, Holmberg M, Shulte M. Binaural hearing aid communication shown to improve sound quality and localization. *Hear J* 2009; 62: 46-7. [\[CrossRef\]](#)
10. Geetha C, Kumar KSS, Manjula P, Mahadevaiah P. Development and standardization of the sentence identification test in the Kannada language. *JHS* 2014; 4: 18-26.
11. Van den Bogaert T, Van Deun L, Klasen T, Moonen M, Wouters J. Horizontal localization with bilateral hearing aids: without is better than with. *J Acous Soc Am* 2006; 119: 515-26. [\[CrossRef\]](#)
12. Ricketts T. Directional hearing aids. *Trends Ampli* 2001; 5: 139-76. [\[CrossRef\]](#)