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Steen Ø. Olsen
Copenhagen University Hospital
Rigshospitalet

Maja Bülow
Audiology Research & Services
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Performance of the SENSO C9 Directional

A field-test study

Many hearing aid users have "better speech understanding in noise" as their number one requirement for a hearing instrument. To feel fully integrated in society, they want to be able to carry on a social or professional conversation, even in acoustic environments with competing noise or reverberation. Even a hearing aid fitted with an optimum frequency response cannot fully compensate for the fact that hearing impaired individuals do need a more favourable signal-to-noise ratio than normal hearing individuals, to obtain an understanding of conversation in noisy surroundings (Plomp 1986).
Directional microphone systems were introduced in hearing aids more than 20 years ago, and have been further developed and implemented in hearing aid series' by a few companies in the industry. By utilizing a technical construction of the microphone (more than one sound inlet) a subsequent signal processing can differentiate sounds coming from different directions. In hearing aids this process is used to suppress sounds coming from the rear.
When studying the performance of directional microphone systems compared to omnidirectional systems through the years, both laboratory research and field-testing have shown several advantages of using directional microphones. In spite of this, the clinical use and dispensing of hearing aids with directional microphones has been very limited in most countries. With the SENSO series, Widex introduced hearing aids containing fully digital signal processors. These processors make continuous analysis of the sound environment, providing automatic changes of the frequency response in 3 bands (independently), providing the user with satisfactory listening comfort and speech intelligibility in both quiet and noisy situations. The research question addressed in this Widexpress 9 is:
What can be achieved with the acoustic features of SENSO in combination with a directional microphone ?

Widexpress 9 addresses the known audiological advantages of hearing aids with directional microphones, and the results of a study made at the Copenhagen University Hospital, Rigshospitalet. In this field test study, experienced hearing aid users were comparing SENSO BTE's with omnidirectional microphones (C8) and directional microphones (C9). The purpose was to investigate their overall satisfaction, and the speech intelligibility in noise they achieved with both types of aids.

As a supplement, this Widexpress also contains a brief introduction to the general working principles of directional microphones.

Audiological advantages of hearing aids with directional microphones

Several early studies with directional microphones showed an improvement in speech intelligibility in noise when the speech signal was presented in front of the subject, 0 degrees, and when the noise was presented from the back at 180 degrees. A recent study by Valente et al (1995) reported an average improvement in signal-to-noise ratio (SNR) of 8 dB when directional microphones were compared to omnidirectional microphones in these ideal listening conditions.

Most studies agree that the measured performance of directional microphones is highest in sound treated booths in laboratories, and that the performance decreases as reverberation in the room increases, and as the distance from the sound source increases. (Among others, Leeuw & Drechsler 1991; Nielsen and Ludvigsen 1978)

Implemented in daily use, hearing aids with directional microphones will provide an advantage over omnidirectional microphones by improving speech intelligibility in reverberant environments and in background noise. The effect is most prominent when the user is close to the sound source (i.e. the speaker). The attenuation of sounds coming from the rear can also provide better listening comfort in noisy environments. Another advantage is that speech intelligibility is enhanced when hearing aids with directional microphones are fitted binaurally (Hawkins and Yacullo, 1984; Leeuw & Drechsler 1991).

Design of the field test at the Copenhagen University Hospital, Rigshospitalet.

The Copenhagen University Hospital, Rigshospitalet, conducted a clinical study investigating if any differences regarding user satisfaction in daily life environments could be found when comparing the performance of two SENSO hearing aids with identical signal processing schemes, equipped with two different microphone characteristics.

The subject group consisted of 22 experienced hearing aid users which had all in the previous 2-4 months been fitted with the SENSO C8, and thereby already were accustomed to the special acoustical features provided by SENSO. The subjects were instructed to use both types of aids in their daily sound environments comparing the sound quality, intelligibility of speech and listening comfort. If a difference between the two aids was noted, the subjects were asked to specify the reason for a possible preference. The subjects were informed that they were testing their own hearing aid (C8) against a new prototype (C9), with another type of microphone. No further explanation about the difference between the two aids was given. The intention was to avoid influence from expectations created by the word "directional", with the potential of causing bias, and simply let the subjects observe the acoustic differences in performance between the C9 with a directional microphone and the C8 with an omnidirectional microphone.
Secondly, the aided psychometric functions in two types of noise with the respective microphones were recorded in a laboratory setup.
A third object of interest was to see if any differences in speech perception performance could be found between monaurally and binaurally fitted subjects.

Of the twenty-two (22) hearing aid users who participated in the test, thirteen (13) were fitted binaurally and nine (9) monaurally. All were full-time hearing aid users, and all but two had more than four years of hearing aid experience.
Audiometric information on fitted ears can be found in Fig 1. Thresholds were all within the very wide fitting range of the C8/C9, including both flat and sloping configurations.
The SENSO C9 was fitted following the same procedure as the fitting of the C8: an initial "Sensogram" was performed, followed by any necessary corrections of HTL, UCL and feedback (Fb) values.

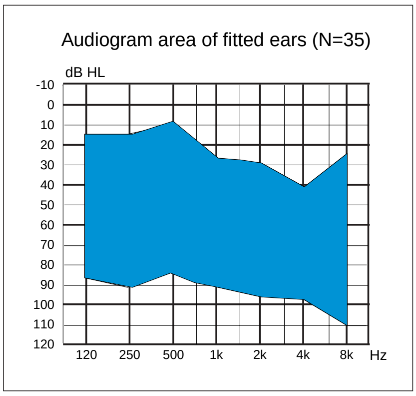

Fig. 1.

The comparison in the field was done by alternately using two sets of aids (C8 and C9 with different microphone characteristics) in the same listening situation and using the same moulds. In order to allow the subjects to distinguish between the two types of hearing aids, C9 aids were marked with a bordeaux coloured nameplate under the battery compartment. All user handling of the two types was identical.
A questionnaire focusing on specific listening situations was handed out and the subjects were asked to report for each situation which of the two aids (if any) they preferred for each situation.
Finally the subjects were asked to give a general comparison of the two aids.
After the field test, which lasted for about 2 weeks, the subjects returned to the clinic with the questionnaires for final evaluation, and to participate in an SIR-test (see below).

Speech Intelligibility Rating (SIR) test; setup and results.

To test how the 22 subjects rated speech intelligibility with different signal-to-noise ratios, wearing the C8 omnidirectional and the C9 directional, we used the concept of the Speech Intelligibility Rating (SIR) test developed by McDaniels and Cox (1989). In the SIR-test procedure each subject is requested to estimate the percentage of words understood in running speech sequences at different signal-to-noise ratios.

A setup with 3 loudspeakers was used in a sound treated booth. The speech signal was presented from 0 degrees azimuth and the noise signal was presented from 90 degrees azimuth on both sides of the subject. (see Fig. 2)

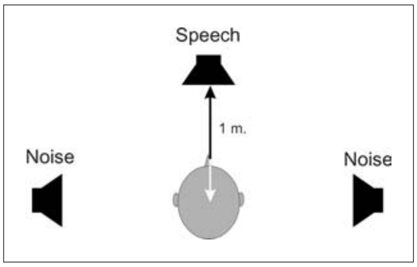

Fig. 2.

This loudspeaker setup was found to be a more realistic example of the "speech in noise" situation in real life environments. Measuring the performance of a directional microphone in background noise from a 90 degree angle, is considered the "average effect" of the two extremes: A. noise presented at 0 degrees azimuth (no effect), and B. noise presented at 180 degrees azimuth (largest effect) (Drechsler & Leeuw 1991). (See also: supplement section on the working principles of directional microphones.) Of course, there will always be a discrepancy between the presentation of environmental noise in real life compared to a sound treated booth, because of the lack of the normal influence of reverberation and/or reflection coming from room acoustics.

The speech signal was excerpts of running speech from the Dantale CD (Elberling et al 1989). It was calibrated after long time RMS to 68 dB SPL, and was recorded on DAT-tape. Two noise types were used: party-noise and car-noise. Each type was recorded on DAT-tape and presented uncorrelated between the two loudspeakers. The presentation level of the speech signal was held constant while the level of the noise signal would increase between each session, starting with 2 dB steps and proceeding to 1 dB steps (see Fig. 3 and Fig. 4). The party noise condition would start with an S/N ratio of +10 dB, and the car noise condition would start with an S/N ratio of 0 dB.

To compensate for a possible order effect, half the group started the SIR test with C8, and the other half with C9.

The results of the SIR test showed a large improvement in the percentage of words understood with C9 directional compared to C8. For the party noise condition (with an S/N ratio of -2 to -5 dB) the mean improvement in intelligibility for the whole group of subjects was 22%. (See Fig. 3) For the car noise condition the mean improvement in intelligibility was 19% (with the S/N ratios -10 to -12). (See Fig. 4)

If we look at the data for the group of binaurally fitted subjects alone, the improvement in party noise was 25%, compared to the group of monaurally fitted subjects who only had an improvement of 17%. For the car noise condition, the mean improvement was 24% for the binaural group, and only 13% improvement for the monaural group (see Fig. 5). This difference in performance between monaural and binaural fittings is consistent with previous findings, supporting the fact that binaural fittings greatly facilitate speech discrimination. (Hawkins & Yacullo, 1984)

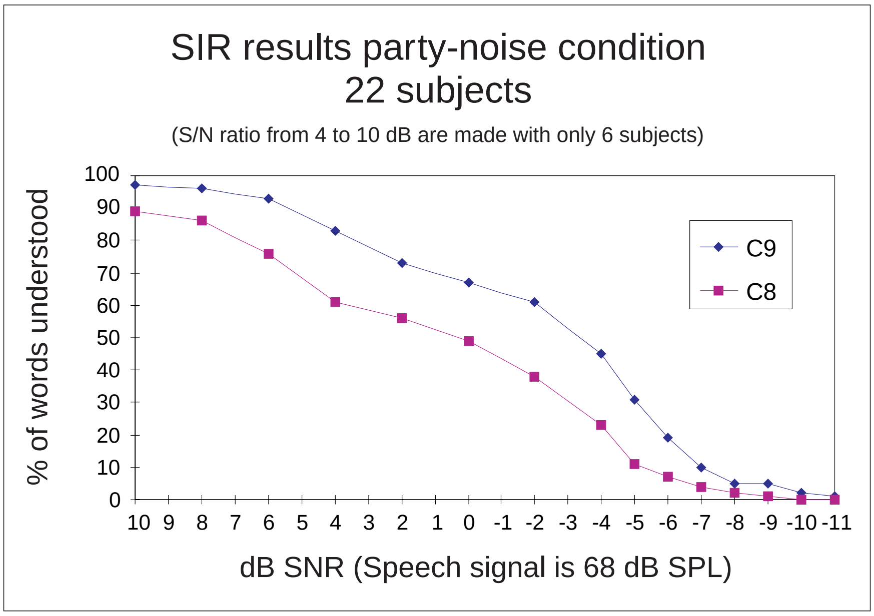

Fig. 3.

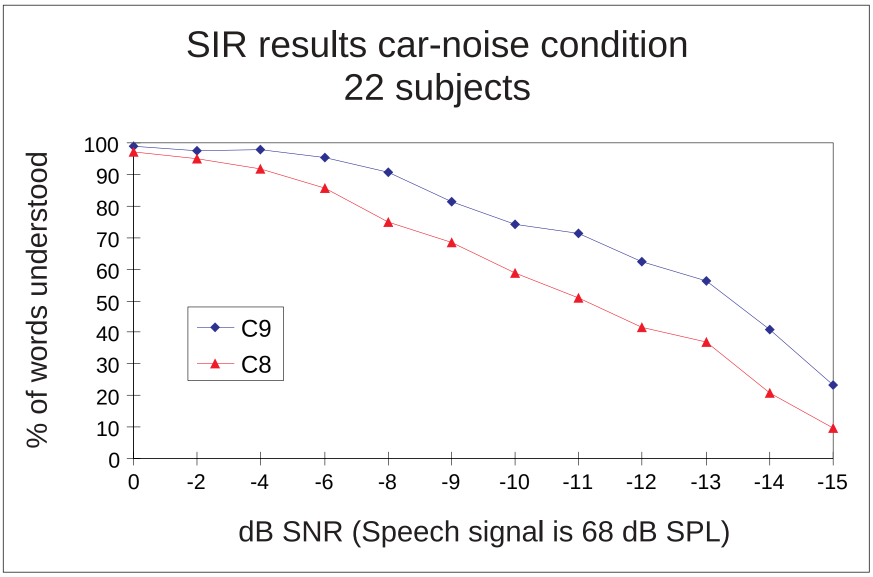

Fig. 4.

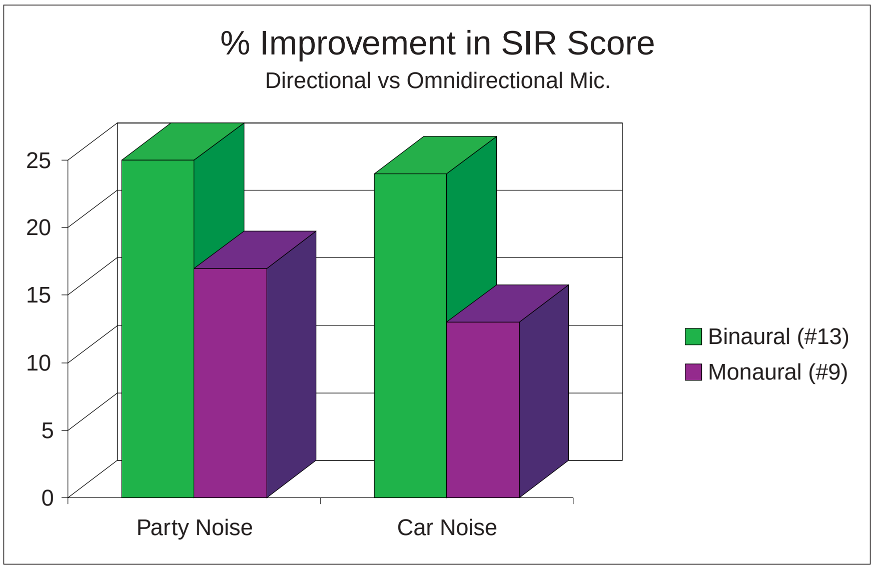

Fig. 5.

Results of the field test and discussion.

After testing the two types of hearing aids in daily life environments, the subjects were asked to make a general rating of the sound quality and performance of the C8 omnidirectional compared with the C9 directional.
Four (4) subjects reported no difference in performance or sound quality between the two aids. Thirteen (13) reported a small difference, and five (5) reported a large difference between the C8 and the C9 (see Fig. 6). There was no significant preference for either of the two types of aids. When asked, eight (8) subjects preferred the C8, nine (9) subjects preferred the C9, and five (5) had no preference. The distribution of monaurally and binaurally fitted subjects according to their answers to these two questions is seen in Fig 6. It appears that the majority of subjects preferring the C9 had been binaurally fitted.

The subjects were asked to test the two types of aids in 12 different sound environments: Quiet conversation in a living room, watching television, listening to music, outdoors in a quiet environment, talking to others outdoors in traffic, riding a bus/ train/car, attending a large social gathering, using household machines, following a conversation around a big dinner table, following a lecture/class, conversation in a bank/office, and in a supermarket. According to the answers in the questionnaire, there was a strong tendency for the subjects to prefer the same type of aid for all listening environments. The group preferring C8 chose this particular aid in nearly all situations, but some of this group even chose the C9 for quiet listening environments such as quiet conversation, TV and music. (See Fig. 7, 8, 9)

For the group of nine subjects preferring C9, it was different. They did not prefer the C8 for any listening situation at all! This means that even when this group of subjects were given the option of alternating between an aid with directional microphone and an aid with omnidirectional microphone, they preferred the directional aid in all listening environments.

The fact that about 45-50 % of the SENSO users in this study preferred the C9 directional in quiet environments apparently disagrees with previous findings. It is a common conclusion that even though directional microphones have shown advantages for improving speech intelligibility in noise, the reduction of low frequency amplification (due to this particular type of microphone) can negatively influence subjects' judgment of the sound quality, especially during conversation in quiet and when listening to music. From research (among others Keidser, 1995) and from our own experience with the different frequency responses in the four programs of the QUATTRO, we know that hearing aid users generally prefer more low frequency amplification in quiet surroundings, and less low frequency amplification in noisy surroundings. A recent study by Kuk (1996) found an impressive improvement in user satisfaction with two-microphone systems, providing there is the possibility of switching between an omnidirectional and a directional microphone position. The study demonstrated that if hearing aid users were given the option of switching between microphone modes, they preferred the omnidirectional mode in quiet listening environments, and when listening to music, sounds coming from behind, or conversation in the next room. The directional microphone mode was preferred when the speaker and the hearing aid user conversed face to face in an noisy environment.

What needs to be considered when discussing the necessity of switchable microphone systems is that by changing from one microphone mode to another, the frequency response is changed as well. The fact that hearing aid users (as demonstrated by Kuk, 1996) show different preferences for directional microphone mode and omnidirectional mode in daily life environments could be due to the difference in frequency response as well as the "directional/omnidirectional effect" of the microphone.

The conclusions of the present study appear to be consistent with the findings above, even though at first glance it looks like a contradiction. There is agreement on the first fact, that different environments require different frequency responses. SENSO addresses this need by performing an automatic change of frequency response as a function of changes in the sound environment. The second fact is that when comparing a directional microphone system with an omnidirectional system, directional microphones significantly improved speech intelligibility in background noise. This finding is constantly supported at different research sites using laboratory setups. A similar improvement in speech intelli-

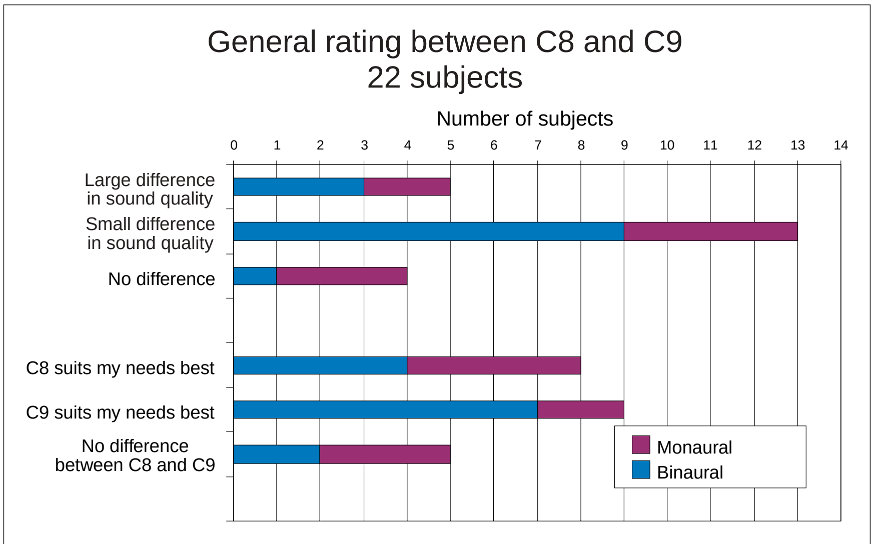

Fig. 6.

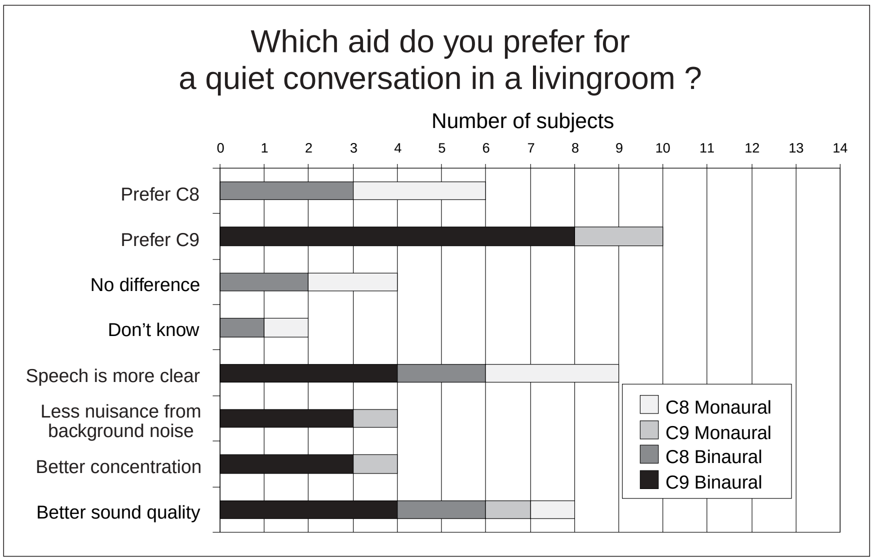

Fig. 7.

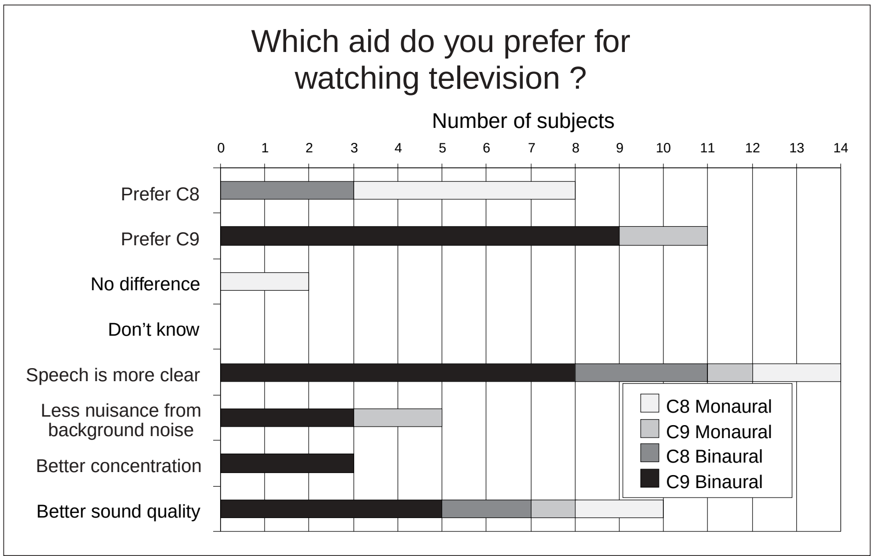

Fig. 8. (Only 21 subjects responded to this question.)

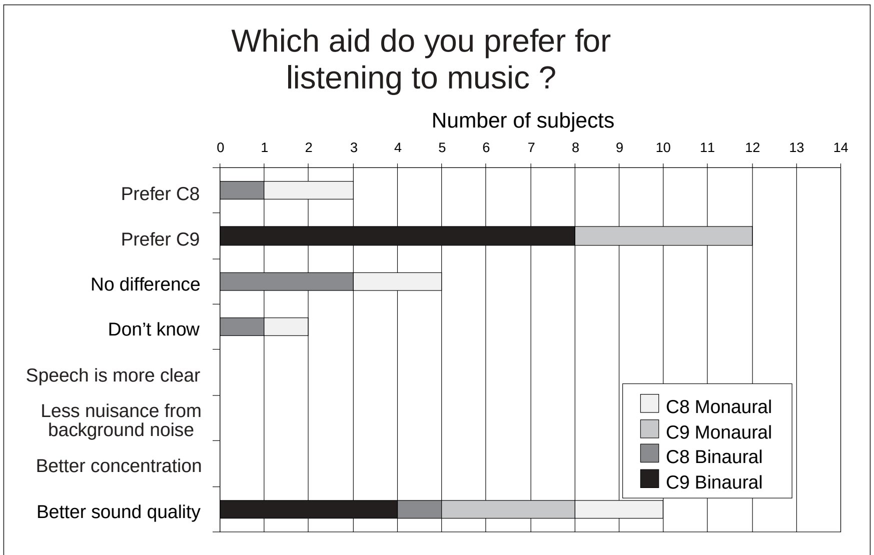

Fig. 9.

gibility could not be found when only comparing performance with different frequency responces. (Valente et al, 1995) The results of the SIR test in the present study show large differences in speech intelligibility scores obtained with two different microphone characteristics, even when the two types of hearing aids utilize the same signal processing. Evidently the directional microphone has an effect of its own.

When looking at the large improvement in speech intelligibility with the C9 directional, we could expect that the subjects would, to a large extent, recognize the advantage of the directional microphone in a noisy environment, and therefore prefer the C9 in these situations. All the subjects preferring the C9 reported that they found the C9 significantly better than C8 in noisy environments, but this is still only 41% of the whole group (the configuration of the hearing loss, or age, could not explain this). The fact that more than half of the test group did not explicitly experience the advantages of the directional microphone in their daily listening environments could be due to the automatic change of frequency response reducing the acoustic differences between the two types of aids. Another reason could be, as reported from double blind field-test studies by Nielsen (1973) and Jensen (1974), that hearing aid users in their daily environments are only to a small extent able to distinguish between hearing aids with directional and omnidirectional microphones. Or it could be that the subjects assess the two types of aids as slightly different, but of equal value. This was a "half-blind" study which means the subjects were not conscious about when and how to expect the C9 directional or the C8 omnidirectional to have the greatest potential. (In the study by Kuk, the subjects knew about the "directional effect").

What should be discussed about the design of this field test is:

1) The subjects were initially used to the sound quality of the C8 omnidirectional.

2) The field test itself was very short, about 2 weeks, which meant that some of the subjects did not find time to try out all the environments.

3) If the subjects were given information about the construction and function of directional microphones (what to test and what to

expect), the results may have looked different.
Consequently, it will be of great importance in future studies with hearing aid users in their own daily environments to investigate the different factors influencing “the directional effect”.

The main conclusions of this study are:

1. SENSO C9 with directional microphone provides a large improvement in speech intelligibility in the two tested types of background noise. This finding is consistent with other studies testing the improvement in signal-to-noise ratios with directional microphones, compared to omnidirectional microphones. (Valente et al 1995, Hawkins & Yacullo 1984, Nielsen & Ludvigsen 1978)

2: Experienced users of the SENSO C8 evaluated the C9. Evidently the (automatic) signal processing provided by SENSO, combined with directional microphones, does not indicate a prominent need for the option of switching between microphones and/or frequency responses.

Directional Microphone Systems

Microphone systems with directional effect can be constructed in various ways, but common for these is the use of multiple sound inlets followed by a certain signal processing to make the system distinguish between sounds coming from different directions.

Generally, the more sound inlets you use, the better performance can be achieved. But in hearing aids where the total size of the aid is of importance, the use of more than two sound inlets is unrealistic.
These two inlets are normally referred to as the front and rear inlets, as they are placed one behind the other, typically at a distance of about 1 cm.

The aim of the signal processing is to attenuate sounds essentially coming from the back and leaving sounds from the front unattenuated.
The simplest yet successful way of doing this is by delaying the signal from the rear inlet and subtracting it from the front signal. If the delay corresponds to the distance between the sound inlets, a sound coming from behind will yield approximately the same phase on either inlet, and the difference will be an attenuated version of this signal. A sound coming directly from the back will be cancelled. Other directional characteristics are possible by using another delay or another distance between the inlets (see Fig. A).
A side effect of this method is that the overall frequency response from a directional microphone basically is tilted 6dB per octave. This means that it will show less sensitivity in the low frequency area, compared to an omnidirectional microphone. Additional filtering can compensate for this.

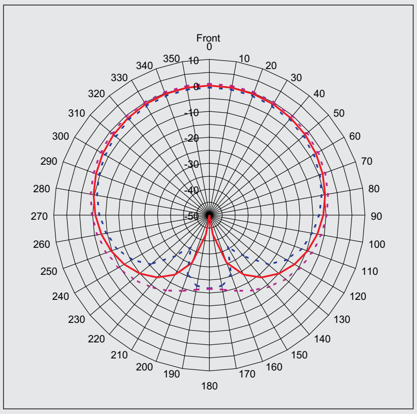

Fig. B.: Free field characteristics for a directional microphone system

When the rear signal delay corresponds to the distance between the two sound inlets, sound directly from the back will be canceled (solid curve).
If the delay or the distance is chosen differently, directional characteristics similar to the dotted curves can be achieved. (See Fig. B.)

When separate microphones are connected to each sound inlet, you have a two-microphone system, where the front and back signals are combined electronically.
This offers the flexibility of performing additional processing before subtracting the front and rear signals. This is, in fact, necessary because the two separate microphone responses need to be exactly alike - and they are not. Another way of solving this problem is by to matching the two microphones during manufacturing and service. The two microphone systems can also be used to provide the option of switching between an omnidirectional and a directional mode. Because of the use of two microphones, total microphone noise is doubled, hence input related noise is increased by 3 dB.

Dedicated directional microphones have two inlets and combine the signals acoustically.
Each inlet leads to a cavity inside the microphone. The two cavities are separated by a diaphragm which reacts to the difference in air pressure in the two cavities, and this reaction is transformed into an electrical signal. An acoustic filter in the rear inlet performs the necessary delay. This acoustic signal processing is not dependent on the microphone response, and it combines the front and rear signals without adding any noise.
The acoustic design of the desired directional characteristic is critical but does not further complicate the circuit. It is done by fine tuning the delay (or the distance between the inlets).

The response of the C9's dedicated directional microphone shows higher sensitivity to input sounds coming from the front (0 degrees), and lower sensitivity to inputs coming from behind (180 degrees azimuth). The frequency response from 0 degrees and 180 degrees sound incidence is called the Front to Back response (Fig. C). The responses were measured when the C9 was in test mode, and in reference test position (IEC 118-0). Here we can see that the attenuation has an average of approximately 20 dB in the whole frequency range from 200 and up to 4000 Hz, which should be

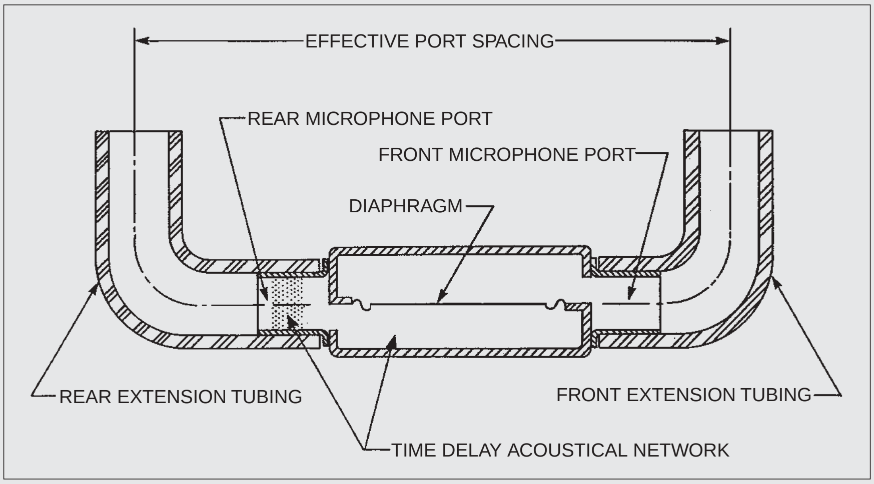

Fig. A.: Dedicated microphone with 2 sound inlets, from Knowles (1989).

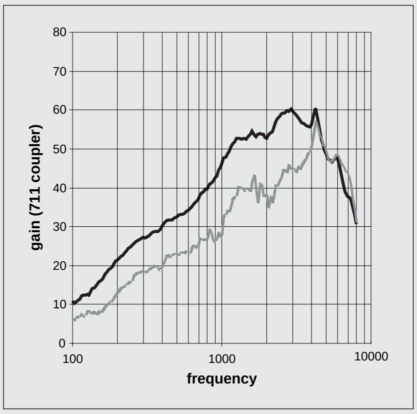

Fig. C.: Front to Back response of the C9.

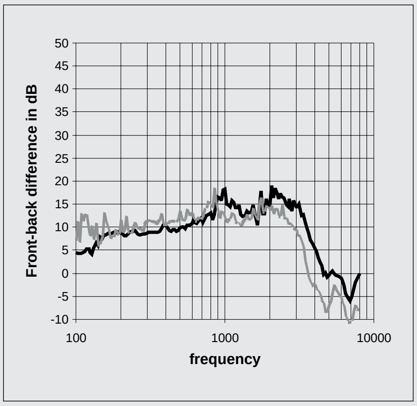

Fig. D.: Front-to-back difference for the C9 (black curve), compared to a well constructed two microphone system.

sidered a very high performance. By subtracting the back response from the front response we get a measure of the Front To Back difference. If we compare the Front To Back difference for the C9, as an exponent for a well constructed single microphone system, to an exponent for a well constructed two microphone system, the two responses show almost equal performance. (see Fig. D)

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