Effect of low-frequency gain and venting effects on the benefit derived from directionality and noise reduction in hearing aids.

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Abbreviations: AI-DI = articulation index weighted directivity index, ANOVA = analysis of variance, BKB = Bamford-Kowal-Bench sentences, BTE = Behind-the-ear, CD = Compact Disc, DI = directivity index, $f_{amplified}$ = frequency at which the amplified region begins, f_{vent} = frequency at which the vent stops transmitting sounds into the ear, HTL = Hearing threshold level, ITE = In-the-ear, ITC = In-the-canal, KEMAR = Knowles Electronics Manikin for Acoustic Research, MPO = Maximum power output, OE/i/ = Occlusion effect for the vocalised /i/ sound, REIG = Real-ear insertion gain, REOIG = Real-ear occluded insertion gain, $REOIG_{own}$ = Real-ear occluded insertion gain for own voice, REUG = Real-ear unaided gain, RMS = Root mean square, SPL = Sound pressure level, SNR = Signal-to-noise ratio, W = Kendall coefficient of concordance, WDRC = Wide dynamic range compression

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ABSTRACT

When the frequency range over which vent-transmitted sound dominates amplification increases, the potential benefit from directional microphones and noise reduction decreases. Fitted with clinically appropriate vent sizes, 23 aided listeners with varying low-frequency hearing thresholds evaluated six schemes comprising three levels of gain at 250 Hz (0, 6, and 12 dB) combined with two features (directional microphone and noise reduction) enabled or disabled in the field. The low-frequency gain was 0 dB for vent-dominated sound, while the higher gains were achieved by amplifier-dominated sounds. A majority of listeners preferred 0 dB gain at 250 Hz and the features enabled. While the amount of low-frequency gain had no significant effect on speech recognition in noise or horizontal localisation, speech recognition and front/back discrimination were significantly improved when the features were enabled, even when vent-transmitted sound dominated the low frequencies. The clinical implication is that there is no need to increase low-frequency gain to compensate for vent effects to achieve benefit from directionality and noise reduction over a wider frequency range.

INTRODUCTION

Wearing a hearing aid invariably requires the insertion of a mould or the actual hearing device into the ear canal in order to deliver amplified sound to eardrum. For many hearing aid users, blocking the ear canal with a tight fitting mold/device leads to the occlusion effect. Occlusion is caused by trapped bone-conducted sounds in the ear canal that can result in increased sound pressure level (SPL) for low-frequency sounds, primarily below 500 Hz, by up to 30 dB (e.g. Wimmer, 1986; Westerman, 1987; Killion, 1988). The effect, which is most commonly produced by one's own voice, is experienced by hearing aid users as "being inside a barrel", or they report that their own voice sounds "hollow and boomy" (e.g. Revit, 1992). Apart from the effect on own voice, occlusion can also result in disturbing noises when chewing, swallowing, breathing deeply, and walking (Courtois et al., 1988). For some individuals the occlusion effect may be so annoying that it can prevent hearing aid usage (Mueller et al., 1996; Kochkin, 2000).

To date the most efficient solution to the occlusion effect is the inclusion of a vent bore in the mould or hearing device (Dillon, 2001), or the use of open moulds (Kiessling et al., 2003; Flynn, 2003) that create a path through which low-frequency sound in the ear canal generated by the bone vibration can escape. The direct sound path through vents or open moulds also allows low-frequency sounds to directly enter the ear canal and mix with the amplified sound (Cox and Alexander, 1983; Dillon, 1991). Although neither the amplified nor the vent-transmitted sound is heard in isolation through a vented hearing aid, it is invariably the case that vent-transmitted sound dominates sound pressure in the ear canal up to the frequency where gain first rises appreciably above 0 dB gain, and amplified sound dominates at frequencies higher than this (Dillon, 2001). Immediately below, at, and above this frequency, sounds arriving via the two paths significantly interact, potentially adding in or out of phase to produce a composite signal significantly affected by both paths.

Apart from relieving the occlusion effect and hence improving the sound quality of the aid wearer's own voice (e.g. Kuk, 1991), there are other possible benefits obtained from vented or open moulds. For example, ventilation is provided to the enclosed ear canal that otherwise may become hot and itchy due to moisture built up in the ear canal resulting, in the worst case, in otitis externa. However, MacKenzie et al. (1989) did not find a significant difference in reported incidents of moist or itchy ears across vent type in 106 clients evaluating an occluding mould, a 0.8 mm vented mould, and a 2 mm vented mould. It is possible that the period (2 weeks) each type of mould was worn was too short to prove a significant benefit from vented moulds for these symptomatic problems. On the other hand, MacKenzie et al. (1989) found that the two vented moulds caused significantly fewer complaints of a sensation of blockage than did the occluding mould. That is, vented moulds contributed to increased comfort when wearing the hearing aids, although it was uncertain whether this was a result of an equilibration of pressure in the residual canal and the atmosphere, or the transmission of environmental sounds through the vent.

The contribution of the direct sound path through the vent can also help overcome problems with audible microphone noise that is found to be objectionable to some hearing aid users with a mild hearing loss, or near-normal hearing, at low frequencies (Macrae and Dillon, 1996; Lee and Geddes, 1998; Agnew, 1998). Finally, at least two studies have reported that vented moulds improved the overall sound quality of hearing aids relative to reducing the low-frequency gain electronically (Cox and Alexander, 1983) and relative to an occluding ear mould (Kuk, 1991). In contrast, Grover and Martin (1979) and Lundberg et al. (1992) failed to find any significant difference in the ratings of perceived sound quality of hearing aid processed sound through vented and occluding moulds. Procedural differences may in part explain the different outcomes.

While vented and open moulds seem to provide some clear benefits to hearing aid users, there are also some potential drawbacks with using such a mould configuration. The sound leakage from larger vents and open moulds can cause feedback, especially when higher gain levels are provided by the hearing device. Fortunately, this issue is decreasing with the development of sophisticated feedback reduction methods, such as phase cancellation (Chung, 2004b).

A current dilemma is that when the low-frequency component of the direct sound path dominates the amplified sound path, the benefit from such features as directional microphones and noise reduction will be limited to the mid and high frequencies. Potentially exacerbating this loss of benefit, directional microphones are sometimes less effective at high frequencies than at low frequencies (Ricketts, 2000; Dillon, 2001; Kuk et al, 2002; Chung, 2004b). In optimum conditions, directional benefit values reported in the literature correspond to changes in the signal-to-noise ratio (SNR) from 5.5 to 11 dB, which translates into a significant improvement in speech recognition in noise (Ricketts, 2001). Therefore, optimising directionality would seem very important. Ricketts (2006) has speculated that performance is decreased by 30%-50% when using directional technology with open moulds. This is partly confirmed by two recent studies in which modern open-fit hearing aids with directional technology were compared to the same device in omnidirectional mode (Fabry, 2006; Flynn, 2004). In both studies the microphones had good directivity in the mid and high frequencies, and in both studies the directional mode provided significant benefits relative to the omnidirectional mode. However, the measured directional benefits of 2.3 and 3.1 dB, respectively, were somewhat less than what has been observed when using occluding moulds. In both studies, the benefit from directional technology with open-fit devices was restricted to speech recognition performance measured in a typical laboratory setup with speech presented from 0° azimuth and noise from the side and the rear. Thus it is still uncertain whether hearing aid users would prefer to compromise the comforts of vent-transmitted low-frequency sound to benefit from advanced hearing aid features, such as directionality and noise reduction, over a wider range of frequencies in their everyday environments. It is also unknown how vent-transmitted and amplified low-frequency sounds, when combined with such advanced hearing aid features, affect performance in other areas, such as sound localisation.

Although impaired localisation is not often recognised by hearing aid users as a problem in everyday life, the importance of being able to correctly determine where sounds are coming from in real-life situations should not be overlooked (Byrne & Noble, 1998). It is widely accepted that interaural time and level differences are dominating cues for left/right discrimination in the horizontal plane, whereas monaural spectral differences are predominant for front/back discrimination (e.g. Middlebrooks and Green, 1991). Both vents and leaks around individually fitted moulds and the signal processing provided by directional microphone and noise reduction have the potential for distorting the interaural difference cues or the spectral differences used for localising sounds in the horizontal plane (Dillon, 2001; Keidser et al, 2006). In particular, two recent studies have demonstrated that directional microphones can affect horizontal localisation performance relative to performance with an omnidirectional microphone (Van den Bogaert et al, 2006; Keidser et al, 2006). Specifically, adaptive directionality or a microphone mode mismatch across ears adversely affected left/right discrimination, while a cardioid microphone characteristic improved front/back discrimination. The latter result was thought to occur because the cardioid microphone had a large positive front-to-back ratio, while the comparison configurations (omnidirectional and figure-8) had front-to-back ratios of nearly zero. In both studies, participants were tested while wearing hearing aids with appropriate vent sizes, but the effect of vent size was not specifically investigated.

The aim of this study was to determine the effect of predominantly vent-transmitted and predominantly amplified low-frequency sounds on hearing aid users' preference and performance when they were fitted with and without a directional microphone and noise reduction. The effect was sought in standard clinical hearing aid fittings using wearable devices and appropriate vent sizes. In a standard hearing aid fitting it is, however, not possible to completely separate the direct vent-transmitted and amplified sound paths. Therefore, by vent-transmitted low-frequency sound we refer to the situation where an insertion gain of 0 dB was produced by vent at low frequencies with the hearing aid gain reduced as much as possible, such that the direct sound path dominated to the greatest degree possible. By amplified low-frequency sound we refer to the situation where hearing aid gain was increased at low frequencies to achieve an insertion gain above the 0 dB gain produced by the vent, such that the amplified path dominated the vent path. The study addressed the following questions:

1) When fitted with advanced hearing aid features, do hearing-impaired listeners prefer positive gain (dominated by amplified sound) to a conventionally prescribed gain of 0 dB (achieved with predominantly vent-transmitted sound) given that the higher gain should widen the frequency range over which benefit from a directional microphone and noise reduction can be achieved?

2) If predominantly vent-transmitted sound, at 0 dB insertion gain, is preferred when a directional microphone and noise reduction are enabled, do hearing-impaired listeners receive benefit from these features even though benefit is limited to the mid to high frequencies?

3) Does either the type of gain (predominantly vent-transmitted at 0 dB versus predominantly amplified with positive gain) or the presence of noise reduction features have any effect on horizontal localisation performance and speech recognition in noise?

Twenty-three listeners with a range of hearing thresholds at 500 Hz participated in the study, all of whom were fitted with appropriate vent sizes to relieve feedback, occlusion, and other mould discomforts. The listeners' subjective preferences in the field and objective performances were further related to simple objective audiological measurements.

METHODOLOGY

Listeners

The listener group comprised 17 males and 6 females whose ages ranged from 39 years to 83 years, with a median age of 76 years. All listeners had a sensorineural hearing loss. A range of low-frequency hearing thresholds was sought and six listeners had a hearing threshold level (HTL) at 500 Hz of 20 dB HL or less. Eleven listeners had a 500 Hz HTL greater than 20 dB HL and less than or equal to 40 dB HL, and 6 listeners had a 500 Hz HTL greater than 40 dB HL. These figures are based on average HTLs measured across ears for bilaterally fitted listeners and the HTL of the fitted ear for unilaterally fitted listeners. The average HTL at 500 Hz was 32.3 dB HL, ranging from 12.5 to 65 dB HL. In each of these three listener groups about two-thirds (16) were fitted bilaterally and one-third (7) were fitted unilaterally. Seventeen listeners had symmetrical hearing loss (no more than a 15 dB gap between ears at any frequency from 250 to 4000 Hz). Two bilaterally and two unilaterally fitted listeners displayed a 20 dB gap at one or two frequencies between 250 and 4000 Hz. However, none of these 21 listeners displayed a gap between the ears at 500 Hz of more than 10 dB. Only two listeners, both unilaterally fitted, had an asymmetrical hearing loss and these two listeners were both fitted on their better ear. All listeners had type A tympanograms at the commencement of the study. Table 1 shows an overview of the listener data.

Due to difficulty recruiting sufficient listeners with a 500 Hz HTL better than 20 dB HL, two listeners (914 and 924) had no prior hearing aid experience. The remaining listeners were experienced hearing aid users who had worn hearing aid/s (ITC, ITE or BTE style) for a minimum of 2.5 years prior to the commencement of the study.

Test device and earmoulds

The test device was a standard Siemens TRIANO S fitted in either BTE or full concha ITE style according to the audiological configuration and preference of the listeners. TRIANO S is a three-memory, 16 channel wide dynamic range compression (WDRC) device. The proprietary fitting software (Connexx, version 4.4) allows gain to be adjusted in 16 frequency channels, and compression, including threshold, ratio, and dynamic behaviour, to be adjusted by four handles, each of them covering four channels. Throughout the study, the dynamic behaviour was set to the default: ‘dual’ for the low frequencies (5 ms attack time and 90 ms release time if level fluctuates suddenly, and 900 ms attack and 1500 ms release time when level fluctuates slowly) and ‘syllabic’ for the high frequencies (9 ms attack time and 90 ms release time). Selective features include microphone directionality (omnidirectional, hyper-cardioid, adaptive), and a noise reduction system that can be disabled or enabled at a minimum, medium, or maximum level. Measured on KEMAR, the directivity index (DI) of the hyper-cardioid microphone varies from 3.5 dB at 1000 Hz to 5 dB at 250 Hz. The articulation index (AI) weighted DI is 4.3 dB. The front-to-side and front-to-back ratios are 9.8 dB and 7.2 dB, respectively. The noise reduction system combines a fast-acting Wiener Filter and a slow modulation-based noise reduction algorithm, both of which manipulate gain in the 16 channels and are designed with the aim of enhancing speech features and reducing noise independently in each band (Hamacher et al. 2005). None of the listeners had prior experience wearing the test device.

For the 16 listeners fitted with BTE devices, new earmoulds were made in hard acrylic (14 listeners) or polysheer (2 listeners) material. Across BTE and ITE wearers the vent size ranged from 1.5 mm to “open” (as large a vent diameter as possible, but which was always greater than 3 mm) configuration as shown in Table 1. For each listener, the vent size was selected according to their 500 Hz HTL and to appropriately control for feedback (3 listeners) and occlusion (2 listeners). Previous experience was also taken into account when choosing the vent size. In all, 9 listeners were fitted with a small vent size (2 mm or less) while 14 listeners were fitted with a large vent size (greater than 2 mm).

Test schemes

Six test schemes comprising three gain-frequency responses by two feature options were implemented. The three gain-frequency responses differed in the amount of real-ear insertion gain (REIG) provided at 250 Hz for a 65 dB SPL broadband, speech spectrum shaped input: 0, 6, and 12 dB, respectively. From 1000 Hz, the REIG responses all matched the NAL-NL1 prescription (Dillon, 1999). The REIG provided at 500 Hz was the interpolation between the gain at 250 Hz and the gain at 1000 Hz. The two feature options included ‘features off’ (omnidirectional microphone characteristic and no noise reduction), and ‘features on’ (hyper-cardioid microphone characteristic and medium noise reduction). While the schemes providing 0 dB REIG at 250 Hz predominantly presented direct vent-transmitted low-frequency sounds, the schemes providing 6 or 12 dB REIG at 250 Hz predominantly presented different degrees of amplified low-frequency sound.

Fitting

Initially, all listeners were fitted with the TRIANO S hearing aid/s according to the NAL-NL1 target with directional microphone (hyper-cardioid) and medium noise reduction. This setting was worn by the listeners in their everyday environments for four weeks, to allow for adjustment to the test device/s. The fitting was verified with REIG measures at 50, 65 and 80 dB SPL input levels using a speech weighted noise signal. During REIG measurements, listeners were positioned at 0 degree azimuth in front of the loudspeaker and the adaptive parameters in the test device were switched off. The maximum power output (MPO) setting selected by Connexx was evaluated by presenting a standard selection of recorded loud noises and asking the listener to rate the loudness using a seven-point categorical scale. The noises included an impulse ‘ping/clang’ noise (75 dB SPL), a steady low-frequency weighted traffic noise (80 dB SPL), and a rattle containing popping corn (85 dB SPL). If any of the noise stimuli were rated as ‘uncomfortably loud’ the MPO was reduced in 3 dB increments until the rating changed to ‘loud but OK’. Finally, continuous discourse was presented at 70 dB SPL. The MPO was to be raised if this speech was reported as sounding distorted; however, this did not occur in any cases.

All listeners attended at least one follow-up appointment during the adjustment period. For 18 listeners some fine-tuning was required in order to achieve a satisfactory fit in terms of comfort and sound quality and to avoid acoustic feedback. When it was established that the ear mould and the amplification were acceptable to the listener for everyday use, the six test schemes were programmed and evaluated with REIG measurements using the same real-ear unaided gain (REUG), i.e. the devices and probe tubes were left in-situ between each set of measures. When programming the different test schemes, it was ensured that 0 dB REIG at 250 Hz was predominantly direct sound by fully reducing hearing aid gain in the two lowest frequency band for this condition, and that previous fine-tuning made to frequencies above 1 kHz was maintained. MPO evaluations were repeated for the schemes providing 12 dB of amplification at 250 Hz and if an adjustment was needed, the procedure was also performed for the scheme providing 6 dB of amplification. The resulting hearing aid settings were stored electronically in the listener’s file under the NOAH fitting system. This allowed the complete range of test schemes to be quickly recalled into the listener’s devices at appropriate times during the test protocol. Measures of REIG and 2cc coupler gain were repeated to confirm that the responses were correct, each time they were recalled for evaluation by the listeners. Figure 1 shows the average 65 dB SPL input NAL-NL1 target and the average REIG achieved at the audiometric frequencies for a 65 dB SPL input across listeners for each test scheme.

Field test

The test schemes were compared three at a time in the field over a four-week period each. Every second recruited listener compared the three ‘features off’ schemes first and the remaining listeners the three ‘features on’ schemes. The assignment of each of the three gain-frequency responses (0 dB, 6 dB, and 12 dB at 250 Hz) against hearing aid programs (1, 2 or 3) was balanced across listeners. After listeners had trialled both the three ‘features off’ and the three ‘features on’ schemes, they compared the most preferred scheme from the first trial to the most preferred scheme from the second trial, for a further two weeks. The assignment of these two schemes to test program 1 or 2 was again balanced across listeners. Throughout the study, the participants were blinded to which schemes they were evaluating.

During the field evaluation, listeners were equipped with structured diary forms that enabled them to rate the performance of each scheme on a 10 point scale (1 labelled ‘very bad’ and 10 labelled ‘very good’) in specific listening situations. The forms also invited the listeners to give a brief description of the performance of each scheme. An example of the diary form is found in Appendix A. To make it possible to compare data across different test periods, each listener was asked to nominate up to six individual listening situations that they experienced on at least a weekly basis. Each listener was asked to nominate at least one situation involving conversation with one other person in quiet, and one situation involving listening in noise. This was done to ensure that there was some similarity in the situations in which the schemes were evaluated across listeners. At the conclusion of each field test, a brief exit interview was carried out. The exit interview investigated the technical performance of devices during the test period, overall usage pattern, overall scheme preferred, and any comments about the schemes trialled; see Appendix A.

Laboratory tests

A set of laboratory tests (paired comparison, speech recognition in noise, and horizontal localisation) was completed by listeners at the conclusion of each of the three field tests. The order in which the laboratory tests were performed was rotated across listeners to reduce any effects of fatigue on one particular test. Prior to each set of laboratory tests the listener's devices were checked (including 2-cc coupler measurement, and visual inspection of the tubing, vents and sound bores) and an otoscopic examination of the listener's ears was performed to exclude the possibility of occlusion by cerumen. During the sequence of test procedures appropriate breaks were given to minimise listener fatigue. Each laboratory test began with a practice session to ensure that the listener understood the task, and to remind the listener about the procedure. The test equipment was calibrated daily.

<u>Paired comparison test:</u> The paired comparison test was conducted in a sound-treated test booth using continuous discourse (male talker) presented at 0° azimuth and babble noise presented synchronously at 90°, 180°, and 270° azimuths. Speech was presented at 65 dB SPL free field and the signal-to-noise ratio (SNR) was +2 dB. Speech and noise were presented from each channel of a CD player (Yamaha CDX-530) through a pair of passive attenuators. From here speech was routed via an amplifier (Yamaha AX-355) to a JBL 4503 AWX-1 loudspeaker. The Noise signal was delivered via amplifiers

(Technics SU-7300) to each of three Aaron Pro 1 loudspeakers. The pairs of loudspeakers facing each other were positioned 2.5 metres apart and during testing the listener was seated in the centre of the loudspeaker array. The schemes just evaluated in the field were compared in a round-robin test ten times. To minimise testing time, each comparison was restricted to an A-B-A comparison where the tester controlled the switching between programs and the listener told the experimenter when to change programs. The experimenter would hold up a card labelled ‘A’ or ‘B’ appropriate to the presentation, and after each comparison, the listener verbally reported which of schemes ‘A’ or ‘B’ was preferred. The order of comparisons and the assignment of schemes to ‘A’ and ‘B’ were balanced across listeners.

<u>Speech in noise test:</u> Using the Bamford-Kowal-Bench (BKB) sentences (Bench & Bamford, 1979) presented in babble-noise, the SNR for which the listener got 50% of key words correct (SNR_{50}) was obtained. The SNR_{50} was measured using the same setup as described above. As in the paired comparison test, speech (male talker) was presented at 0° azimuth and babble noise synchronously at 90°, 180°, and 270° azimuths. The speech level was fixed at 65 dB SPL free field, and an adaptive procedure for adjusting the noise level was used to determine the SNR_{50}. After the first two field tests, speech in noise performance was measured for the two responses including the minimum and maximum REIG at 250 Hz (i.e. 0 and 12 dB) whereas the speech test was performed after the third field test using the two combinations of gain and features that were just evaluated. The order of schemes was balanced across listeners and the selected BKB lists were balanced

across schemes. One sentence list (comprising 16 sentences) was used for each scheme to determine the SNR_{50}.

<u>Horizontal localisation test:</u> Horizontal localisation performance was measured using a 360 degree loudspeaker array arranged in an anechoic chamber with internal dimensions of 6 x 3.9 x 4.5 m. The array consisted of 20 loudspeakers positioned 18 degrees apart, which were covered with an acoustically transparent cloth so that the number of loudspeakers and their position were unknown to the listeners. Bursts of pink noise were presented at 65 dB SPL free field with a randomly applied ± 3 dB rove in level. For further details of the test setup; see Keidser et al. (2006). During testing, the listener was seated in the centre of the array with the ears at the same height as the loudspeakers. After each presentation, the listener verbally reported the perceived direction of the stimulus in degrees. Direction was shown in 10 degree intervals on the cloth covering the loudspeakers and the listener held a chart showing angle numbered in 10 degree intervals. The listener's head position was controlled during sound presentation by fitting the listeners with a head lamp and instructing them to maintain the beam of the light in the centre of the 0° marker in front of them. A video link enabled the experimenter to monitor the listener's head position during testing. As for the speech test, horizontal localisation performance was only measured for the schemes including the minimum and maximum REIG at 250 Hz (i.e. 0 and 12 dB) after the first two test periods, whereas the test was performed after the third test period using whichever two schemes were evaluated in the field. The order of schemes was again balanced across listeners and for each scheme there were two presentations from each of the 20 loudspeakers presented in

a random fashion. From the forty responses, the RMS error was calculated independently for the left/right and front/back dimensions, as outlined in Good & Gilkey (1996).

Objective measurements

For each listener the real-ear occluded insertion gain (REOIG) of the vent-transmitted sound and the occluded insertion gain of the listener's own voice ($REOIG_{own}$) were measured. The REOIG was measured as the difference between the response with the device/s inserted but switched off and the open ear response using a broadband speech shaped noise as stimulus and a 65 dB SPL input level. The REOIG was exported from the real-ear analyser and the frequency at which the vent stopped transmitting sounds into the ear canal without significant attenuation was extracted (f_{vent}). This frequency was defined as the lowest frequency at which the REOIG fell below -3 dB.

The $REOIG_{own}$ was obtained in a similar manner, but with the stimulus level of the insertion gain analyser turned right down while having the listener vocalising an /i/ during the recording of the open ear response and the response obtained with the device/s inserted and switched off. The listeners observed their voice level on a sound level meter in front of them to ensure that the vocalisation was constant around 80 dB SPL both for the unaided and aided measurement. From the exported $REOIG_{own}$, the occlusion effect for /i/ (OE/i/) was obtained by averaging the $REOIG_{own}$ values across the frequencies from 125 Hz to 1000 Hz. One listener (913) did not complete these measurements due to feeling unwell at the last appointment when the measurements were obtained. For another listener (925) the exported file with the $REOIG_{own}$ data got corrupted.

Finally, from the exported REIG response measured for the 0 dB/features off scheme, the frequency at which the amplified region begins was extracted ($f_{amplified}$). This frequency was defined as the lowest frequency at which the REIG response exceeded 3 dB.

RESULTS

Vent effects

A correlation analysis was performed to investigate the correlation between vent size and f_{vent}, $f_{amplified}$, and OE/i/. In this analysis, a value of 3.5 mm was assigned to the two listeners who were fitted with an 'open' vent. Both f_{vent}, and $f_{amplified}$ were moderately and significantly correlated to the vent size (Spearman $R = 0.52$, $p < 0.05$ and Spearman $R = 0.71$, $p < 0.001$, respectively), increasing with increasing vent size; see Figure 2a. The correlation between the vent size and OE/i/ was weaker and not significant (Spearman $R = -0.20$, $p = 0.39$), where the negative sign indicates that the occlusion effect was greater for listeners fitted with smaller vent sizes, Figure 2b. Overall, vent effects were as expected; however, there were some variations in data that may be explained by the depth of the individual mould or aid, leakage, and individual bone conduction transmission characteristics.

Preference in the field

During the study, the preference for each test scheme was monitored in two different ways; partly by asking the listener in the exit interview which program was most liked overall and partly by having the listener rate the performance of each scheme in different listening situations during the field trial. From the diary forms, the average performance rating allocated to each of the six test schemes was calculated for each listener. Across listeners and three test periods, the scheme that got the highest performance rating was consistent with the scheme that was nominated as winner in the exit interview in 91% of cases. Data from one listener (908) showed inconsistency between reported preference and the diary ratings in all three test periods. At the end of each test period, this listener reported a preference for 0 dB/features on, 12 dB/features off, and 12 dB features off, respectively, while the highest rating in the diary was given to 6 dB/features on, 6 dB/features off, and 0 dB/features on. These cases accounted for half of the total number of inconsistent cases. Consequently data from listener 908 were considered unreliable and they were excluded from the further analyses.

Based on the response to the exit interview and the measured REIG at 250 Hz, figure 3 shows the gain preferred at 250 Hz when the features were enabled vs. when the features were disabled. When the features were enabled, 17 listeners preferred 0 dB gain, three preferred 6 dB gain, and two preferred 12 dB gain at 250 Hz. When the features were disabled, 15 listeners preferred 0 dB gain, four preferred 6 dB gain, and three preferred 12 dB gain. According to a Chi-square test, the observed listener distribution across gain setting was significantly different from that expected by chance ($\chi^2 = 19.3$, $p < 0.00007$ and $\chi^2 = 12.1$, $p < 0.002$, respectively). Overall, the listeners preferred the same amount of gain at 250 Hz whether the features were enabled or disabled. Only five participants preferred different levels of gain at 250 Hz for the two test conditions, with one participant selecting higher gain when the directional microphone and noise reduction were enabled.

Of the 14 listeners who chose 0 dB gain at 250 Hz whether the features were enabled or disabled, 12 preferred the ‘enabled’ scheme after the third and final test period. In all, 19 listeners preferred the ‘enabled’ scheme when compared to a ‘disabled’ scheme, 15 of whom preferred 0 dB gain at 250 Hz. The distribution of listeners across the two signal processing conditions was significantly different from the distribution expected by pure chance ($\chi^2 = 11.6$, $p < 0.0006$).

Figure 4 shows the average performance rating assigned to each scheme in the field during test periods 1 and 2. On average, the performance was rated lower as the gain at 250 Hz increased. Further, the performance of the ‘features on’ schemes was, on average, rated higher than for the corresponding ‘features off’ schemes. The performance ratings were used as observations in an analysis of variance (ANOVA) for repeated measurements using features (enabled, disabled) and gain (0, 6, 12 dB) as repeated measures. A further two listeners were excluded from this analysis since their rating data were incomplete (missing for one and three schemes, respectively). The analysis revealed a significant effect of both features and gain ($F_{1,19} = 7.1$, $p = 0.02$ and $F_{2,38} = 22.2$, $p < 0.0000001$, respectively). The performance of the ‘features on’ schemes was rated significantly higher (rating = 6.0) than for the ‘features off’ schemes (rating = 5.3). A post hoc analysis of means (Newman Keuls) showed that schemes providing 12 dB insertion gain at 250 Hz were rated significantly lower (rating = 4.1) than the schemes providing 0 dB (rating = 6.8) and 6 dB (rating = 6.0) insertion gain at 250 Hz ($p = 0.0001$ and $p = 0.0002$, respectively). The interaction between features and gain was not significant ($F_{2,38} = 0.2$, $p = 0.81$).

Separate analyses were also conducted using degree of hearing loss at 500 Hz (≤ 20 dB HL, > 20 dB HL and ≤ 40 dB HL, > 40 dB HL), vent size (≤2.0 mm, >2.0 mm), aid configuration (unilateral, bilateral), and type of device (BTE, ITE) as between group factors. None of the between-group factors showed significance ($F_{2,17} = 0.3$, $p = 0.77$; $F_{1,18} = 0.03$, $p = 0.86$; $F_{1,18} = 0.5$, $p = 0.51$; and $F_{1,18} = 0.9$, $p = 0.36$, respectively) or changed the outcome above.

In the third test period where the listeners compared their preferred ‘features on’ scheme with their preferred ‘features off’ scheme, the average performance ratings were 7.8 and 6.8, respectively. According to a t-test for dependent variables the difference in performance rating was significant ($t_{21} = 3.4$, $p = 0.002$).

An analysis of individual listening situations showed that the preferred ‘features on’ scheme, on average, was rated higher than the preferred ‘features off’ scheme for a wide range of situations, including one-to-one conversation in quiet (N = 22), one-to-one conversation in noise (N = 9), watching TV (N = 19), group conversation in significant background noise (N = 9), listening to church service (N = 8), and being in a noisy environment (N = 8). However, the difference in performance rating was greater when listening in noise and reverberation (1.8 units on average) than when listening in quiet

(0.6 units on average). The difference was even smaller (on average 0.1 units in favour of the 'features on' scheme) when listening to music, although the number of reports on such a situation was rather small ($N = 5$).

Preference in the laboratory

The number of times a scheme was preferred over the other schemes in the paired comparison test is referred to as a preference score. Figure 5 shows the average preference score assigned to each scheme after each paired comparison test. According to a Friedman two-way analysis of variance test, the preference scores differed significantly across conditions ($p < 0.01$) in each paired comparison test. Both when comparing the 'features on' and the 'features off' schemes, the scheme providing 0 dB REIG at 250 Hz was the most frequently preferred scheme, followed by the schemes providing 6 dB and then 12 dB REIG at 250 Hz. When comparing the preferred 'features on' scheme with the preferred 'features off' scheme, the tested 'features on' scheme was the most preferred. In the first two tests, the Kendall coefficient of concordance (W), which expresses the degree of agreement between listeners and ranges from 0 to 1, was rather low (0.34, and 0.19 respectively). However the sums of squares of the observed deviations from the mean of the sum of ranks (s) were in both cases greater than the critical value for the 5% level of significance, $s(3,22) \approx 143.8$ ($s = 325.5$ and $s = 171.5$, respectively); see Siegel (1956). In the last test W was rather high ($W = 0.77$), so generally the order of preference was somewhat consistent across listeners. These results are in excellent agreement with the field test results.

Relationship between preference and objective measurements

For each listener the achieved REIG value at 250 Hz was extracted for the overall preferred scheme. No significant correlation was found between the amount of low-frequency gain preferred at 250 Hz in the field and a range of audiological measures, including the HTL at 250 Hz and 500 Hz, the average HTL measured across 250, 500, and 1000 Hz (LFavg), the average HTL measured across 2000, 3000, and 4000 Hz (HFavg), the NAL-NL1 target at 250 and 500 Hz, vent size, f_{vent}, $f_{amplified}$, and OE/i/; see Table 2. This is presumably because of the large number of listeners who chose 0 dB gain at 250 Hz, limiting the spread in data across preferred REIG at 250 Hz.

Speech recognition in noise and horizontal localisation performance

All the participants completed the speech recognition in noise test for four of the test schemes: 0 dB/features on, 12 dB/features on, 0 dB/features off, and 12 dB/features off. A repeated measures ANOVA using SNR_{50} as the observation and features and gain as repeated measures showed a significant effect of features ($F_{1,21} = 26.9$, $p = 0.00003$). The average SNR_{50} was significantly lower when the features were enabled (-0.2 dB) than when the features were disabled (2.4 dB). That is, in the noise configuration used in this study the listeners performed better when fitted with directional microphone and medium noise reduction. Neither gain nor the interaction between the main factors showed significance ($F_{1,21} = 3.7$, $p = 0.07$; $F_{1,21} = 0.04$, $p = 0.85$, respectively). Separate analyses using degree of hearing loss at 500 Hz, vent size, aid configuration, and type of device as between-group factors revealed a significant interaction between features and type of device ($F_{1,20} = 5.8$, $p = 0.03$). The directional benefit of -3.3 dB for the BTE wearers was significant, while the directional benefit of -1.0 dB for the ITE wearers was not (Figure 6). None of the other between-group factors showed significance ($F_{2,19} = 1.4$, $p = 0.26$; $F_{1,20} = 3.1$, $p = 0.09$; and $F_{1,20} = 0.004$, $p = 0.95$ for degree of hearing loss at 500 Hz, vent size, and aid configuration, respectively), or changed the overall result.

Horizontal localisation testing was completed for the same four test schemes. For one listener (916), the data file for one scheme was accidentally overwritten before the RMS errors were extracted. Consequently, the following analyses are based on data from 21 listeners. In the left/right dimension, a repeated measures ANOVA showed no significant effect of features ($F_{1,20} = 0.6$, $p = 0.46$), gain ($F_{1,20} = 1.1$, $p = 0.31$), or the interaction between the two main factors ($F_{1,20} = 0.004$, $p = 0.95$). Repeating the analysis using degree of hearing loss at 500 Hz, vent size, aid configuration, or type of device as between-group variables revealed a significant effect of aid configuration ($F_{1,19} = 7.3$, $p = 0.01$). Listeners who were fitted unilaterally produced significantly higher left/right RMS errors (34.5° on average) than those who were fitted bilaterally (17.6° on average), (Figure 7). Some of the unilaterally fitted listeners showed a very strong bias of responses toward their aided ear. None of the other between-group factors showed significance ($F_{2,18} = 1.5$, $p = 0.26$; $F_{1,19} = 2.0$, $p = 0.17$; and $F_{1,19} = 0.9$, $p = 0.35$ for degree of hearing loss at 500 Hz, vent size, and type of device, respectively), or changed the overall result.

In the front/back dimension, there was again a significant effect of features (($F_{1,20} = 7.1$, $p = 0.01$), but no significant effect of gain ($F_{1,20} = 1.3$, $p = 0.26$) or interaction between features and gain ($F_{1,20} = 0.5$, $p = 0.50$). On average, the listeners made more errors when tested with the features disabled (64.2°) than when tested with the features enabled (57.2°). None of the between-group factors (degree of hearing loss at 500 Hz, vent size, aid configuration, or type of device) showed significance ($F_{2,18} = 1.0$, $p = 0.37$; $F_{1,19} = 1.8$, $p = 0.20$; $F_{1,19} = 0.02$, $p = 0.88$; and $F_{1,19} = 4.2$, $p = 0.054$, respectively), or changed the overall result. However, the effect of device type approached significance as BTE wearers, on average, produced higher front/back errors (63.8°) than did ITE wearers (53.0°); see Figure 8.

Seventeen listeners performed the SRT and localisation tests twice with the 0 dB/features on scheme. A t-test for dependent variables revealed no test-retest effects for SNR_{50} and the left/right RMS error ($t_{16} = 0.5$, $p = 0.62$ and $t_{16} = 0.82$, $p = 0.42$, respectively). However, the listeners produced a small, but significantly higher front/back RMS error ($t_{16} = 2.62$, $p = 0.02$) at the last appointment (58.7°) than at the earlier appointments (54.5°).

DISCUSSION

Comparison of three levels of amplified low-frequency sound showed an overwhelming preference in real life for vent-dominated, 0 dB REIG at 250 Hz, relative to either 6-dB or 12-dB gain dominated by amplified sound. The strong preference for vent-dominated, 0 dB low-frequency sound was independent of the presence or absence of directional microphone and the noise reduction feature. Only one participant (925) selected higher gain when the features were enabled than when the features were disabled. When the listeners compared their preferred responses for ‘features on’ and ‘features off’, 19 listeners out of 22 selected the scheme in which the features were enabled, including 14 who selected 0 dB REIG at 250 Hz in both conditions. Prior to commencing the study we had speculated that when the features were disabled, the participants would select a scheme with the amount of low-frequency gain that most closely resembled the NAL-NL1 prescription while they would select more low-frequency gain when the features were enabled to receive greater benefit from the directional microphone and noise reduction. We therefore found it surprising that so many listeners preferred the 0 dB gain scheme with predominantly vent-transmitted low-frequency sound to the higher gain schemes with predominantly amplified sound, as the former restricted the frequency range over which the directional microphone and the noise reduction feature could provide benefit.

As the low-frequency gain increased from the 0 dB condition to the 12 dB condition in this experiment, four things changed, all of which could have influenced the choice the listeners made.

1. The tonal balance of the sound changed as the high-frequency emphasis of the gain-frequency response became less marked.
2. The low-frequency sound changed from being predominantly vent-transmitted sound (with no non-linear distortion, no internal noise, and linear amplification) to predominantly amplifier-processed sound (with some non-linear distortion, some internal noise, and whatever compression characteristics the aid was prescribed with).

3. The interaural time difference (ITD) that is important for left/right discrimination may have become more distorted due to the delay caused by the amplifier-processed sound and its interaction with the vent-transmitted sound.
4. When the features were enabled, the directional microphone and noise reduction operated over a wider frequency range, which in theory should provide additional benefit.

Tonal balance and sound quality

Some studies have demonstrated that when listeners rate the sound quality or pleasantness of speech in quiet shaped with different filters, they often prefer the filter with the flatter response shape or the filter that provides most gain at low frequencies (Harford and Fox, 1978; Punch et al., 1980; Gabrielsson et al., 1988; Keidser, 1995a). On the other hand, Harford and Fox (1978), Keidser et al. (1995) and Keidser et al. (2005) found that a low-frequency cut relative to the filter shape preferred for listening to speech in quiet was preferred when listening to speech in background noise, especially low-frequency weighted noise. Given that most listening environments introduce some degree of background noise and that most common stationary background noises are low-frequency weighted (Keidser, 1995b), the tonal balance could have had an influence on the listeners' preference for less insertion gain at 250 Hz. It is further possible that some listeners may have experienced less adverse effects from upward spread of masking with the schemes that provided less amplified gain at 250 Hz (e.g. Harford and Fox, 1978; Fabry et al., 1993; van Buuren et al., 1995)

The strong preference for 0 dB gain at 250 Hz could also be explained by the listeners experiencing less distortion or internal noise from the test device (e.g. Dillon et al., 2003; Chung, 2004a), which may have improved the overall sound quality. However, the results of Lundberg et al (1992) suggest that simply changing from vent-transmitted sound to amplifier-processed sound has little direct consequences on the overall perceived sound quality.

Benefit from directional microphone and noise reduction

Ricketts (2000) has demonstrated that the DI at 500 Hz of a directional microphone decreases as vent size increases, presumably because of decreasing dominance of the amplified sound path. We also measured the DI of the test device when in directional microphone mode. The measurements were done on KEMAR in an anechoic chamber using a BTE device. Measurements were obtained at various frequencies, including 250 Hz, using the three average gain-frequency responses (with 0, 6, and 12 dB gain at 250 Hz, respectively) fitted to the listeners in each of the three listener groups. Three vent sizes (3.5, 2.5, and 2.0 mm) were used, one for each group, respectively. The measurements confirmed that when the REIG at 250 Hz was 0 dB, i.e. the direct sound path was dominating, there was no benefit from the directional microphone at this frequency, and that the DI increased with increasing gain, Figure 9. This is not a surprising result. Directivity relies on achieving an accurate cancellation of sounds arriving at the ear. When the amplified sound is at a much higher level than the vent-transmitted sound, a low sensitivity to the rear will be achieved when the sounds arriving at each microphone port are appropriately cancelled. When the vent-transmitted sounds are significant, there are three sound paths that must be appropriately combined if good directivity is to be achieved. When the amplified sound is only 6 dB above the vent-transmitted sound, it is likely that the vent-transmitted sound will be of sufficient magnitude to significantly reduce directivity. Similarly, although this was not measured, one can assume that gain reduction at low frequencies produced by the noise reduction algorithm was more effective the more the amplified sound dominated the direct vent transmitted sound. As the directional microphone and noise reduction were either both enabled or disabled, it was the combined effect of the two features that affected preferences. Note that Figure 9 displays gain values obtained at 250 Hz greater than 6 and 12 dB. These gain values were obtained on KEMAR in an anechoic chamber and they were higher than equivalent REIG measurements performed on KEMAR in the test booth where the study participants were fitted with the test devices. The discrepancy between the two sets of measurements was probably seen because the test booth measurements would reflect sensitivity from all directions, which was not as high as frontal sensitivity.

According to the subjective performance rating of the two schemes, the overall preference for the features enabled over the features disabled seemed to be related in particular to improved speech understanding in noisy and reverberant listening environments. The relationship was supported by performance on the objective tests, in which the listeners performed significantly better in the speech-in-noise test and produced significantly fewer localisation errors in the front/back dimension when the features were enabled, even when the low-frequency information was predominantly vent-transmitted sound. This would suggest that there was sufficient benefit from directional microphones and noise reduction in the mid and high frequencies for the range of low-frequency hearing losses and vent sizes tested in this study.

It should be noted that the significantly higher directional benefit for speech recognition in noise that was observed for BTE wearers compared to ITE wearers was caused by poorer performance by the BTE wearers with the test aid in the omnidirectional mode (Figure 6). This finding is in agreement with results presented by Pumford et al (2000) and Ricketts et al (2001). Further, the overall average directional benefit of 2.4 dB measured in this study is in agreement with Flynn (2004) and Fabry (2006), who measured the directional benefit obtained with modern open-fit hearing aids, and it is lower than typical benefit values reported for closed moulds (Ricketts, 2001).

There was no significant effect of low-frequency gain on horizontal localisation performance, especially in the left/right dimension, which presumably reflects the fact that audibility of the low-frequency information of the test stimulus was sufficient in both the 0-dB gain and 12-dB gain conditions, and whether features were on or off. The significantly poorer left/right discrimination by unilaterally fitted listeners compared with the bilaterally fitted listeners seen in this study is not necessarily in conflict with Byrne et al. (1992) who found a bilateral advantage only for the more severely impaired listeners (4FA HTL > 50 dB HL). As pointed out in Byrne and Noble (1998), the effect of aid configuration is rather complicated and depends on many and varied factors, such as hearing threshold level across ears, experience with amplification, and central auditory function. We note that all the unilaterally fitted participants in this study wore BTEs while half of the bilaterally fitted participants wore ITEs and the other half wore BTEs. On average, the participants fitted with BTEs had a higher degree of hearing loss (4FA

HTL = 47.2 dB HL) than those fitted with ITEs (4FA HTL = 43.8 dB HL), but more significantly the unilaterally fitted listeners displayed, on average, a larger asymmetry (13.6 dB) between ears than did the bilaterally fitted listeners (3.5 dB).

Listeners in this study demonstrated improved front/back discrimination when a directional hyper-cardioid microphone with a positive front-to-back ratio was used (Figure 8), which is in agreement with Keidser et al (2006). Keidser et al (2006) also found a significant change in front/back discrimination over time when the listeners were tested with a directional microphone with a positive front-to-back ratio (a cardioid microphone). However, in that study, the performance improved. The reason for the deterioration in performance over time in the front/back dimension that was seen in this study is unknown.

Because of the inevitable, but realistic, confounding of type of sound transmission (vent-dominated versus amplifier dominated) with the amount of low frequency gain, it is not possible to interpret the results as being simply due to the type of sound transmission or amount of gain. Our interpretation of the findings is that the strong majority preference for 0 dB gain, vent-dominated, low-frequency sound at 250 Hz when the features were on arose from the following combination of factors: 1) 12 dB gain, although sufficient to ensure directivity and effective operation of the adaptive noise reduction algorithm, provides more low-frequency gain than the listeners prefer, 2) 6 dB gain allows some directivity and noise reduction to remain at low frequencies, but the amount is not sufficient to compensate for the low-frequency gain being greater than the listeners prefer, and 3) the improvement in intelligibility offered by directionality at low frequencies is small, compared to the high frequencies, because of the low contribution to intelligibility that is provided by low frequency information (Ricketts et al., 2005). Consequently, the preference for 'features on' compared to 'features off' is likely due to the effects of directivity and noise reduction across the mid and high frequencies.

Prediction of preference

At the conclusion of the study, five listeners preferred amplified low-frequency sound either with the features disabled (907) or enabled (903, 911, 913, and 916). No objective measurements related to audiometric data, vent effects, or prescribed gain could reliably explain the preference for low-gain or high-gain low-frequency sound for individual listeners. In particular, it should be noted that there was no correlation between preferred gain at 250 Hz and that prescribed by NAL-NL1. However, the five listeners choosing higher gain, amplifier-dominated, low-frequency sound, on average, had a significantly ($p = 0.03$) greater HTL at 500 Hz (43 dB HL) than those who preferred 0 dB gain, vent-dominated, low-frequency sound at 250 Hz (28 dB HL); see Figure 10. Although the trend is in the expected direction, and agrees somewhat with Ricketts and Henry (2002), who found that gain compensation in directional hearing aids was needed for listeners with a low-frequency hearing threshold greater than 40 dB HL, the finding should be interpreted with some caution. This is because the number of listeners with an HTL > 40 dB HL at 500 Hz was proportionally much smaller than the number of listeners with a mild hearing loss at 500 Hz.

Occlusion effect and vent size

While there were significant correlations between the fitted vent size and objective measurements related to the vent-transmitted sound (f_{vent} and $f_{amplified}$), we saw no significant correlation between the objective measures of the individual occlusion effect (OE/i/) and vent size. We also found that for half of the listeners who were fitted bilaterally with the same vent size on both ears, there was a difference in OE/i/ measured across ears of 5 to 10 dB. This could be because such measurements are unreliable, as suggested by for example Kampe and Wynne (1996) and Kiessling et al. (2005), or it could be related to the depth of the individual mould or aid, variations in leakage around the mould, variations in bone-conducted transmission to the ear canal, or a combination of all three (Dillon, 2001).

CONCLUSIONS

When fitted with a directional microphone and noise reduction in conjunction with appropriate vent sizes to relieve occlusion, feedback, and other mould discomforts, the participants in this study generally preferred predominantly vent-transmitted low-frequency sound, at 0 dB insertion gain, to predominantly amplified low-frequency sound at higher gain levels that would allow them to receive benefit from directionality and noise reduction over a wider range of frequencies.   The preference for predominantly vent-transmitted low-frequency sound was significant both in everyday environments and in a paired comparison test. Out of 22 participants, 19 preferred the features enabled in the field, including 15 listeners who preferred predominantly vent-transmitted low-frequency sound (0 dB insertion gain at 250 Hz) for the features-enabled condition. Five listeners who preferred predominantly amplified low-frequency sound at the end of the study tended to have a higher degree of hearing loss at 500 Hz. The amount of low-frequency gain had no significant effect on horizontal localisation performance or speech recognition in noise. However, the listeners showed a significant benefit in front/back discrimination and speech recognition in noise from having the directional microphone and noise reduction enabled, even when these features were effective only across the mid to high frequencies. On this basis, we recommend that at those frequencies where the target insertion gain is about 3 dB or less, there is no need to increase gain at low frequencies to compensate for vent effects to achieve more benefit from features like directional microphone and noise reduction. At those frequencies where the target gain is greater than about 3 dB, however, it is desirable to compensate for the vent effects, otherwise the required gain target will not be reached.

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APPENDIX A

Diary form

Your listening situation: Date:

1) Performance rating Program 1 (one beep): (Scale from 1 to 10 with 1, 5, and 10 labelled Very bad, OK, and Very good, respectively)
2) How would you describe the performance of Program 1:
3) Performance rating Program 2 (two beeps): (Scale from 1 to 10 with 1, 5, and 10 labelled Very bad, OK, and Very good, respectively)
4) How would you describe the performance of Program 2:
5) Performance rating Program T (three beeps):
6) How would you describe the performance of Program T:

Exit interview:

Participant ID/Date/Conclusion of test period

1) Aid usage during this test period (8 hours per day+/4-8 hours per day/1-4 hours per day/not every day)

2) Any problems with the test device during the test period? (e.g. performance, technical, feedback, comfort)

3) Did the programs sound different to you? How much (distinct/moderate/slight)

4) Which program did you like most overall? Comments?

Table 1: Overview of listener data.

				Left ear (dB HL)						Right ear (dB HL)					
Listener	Age (years)	Fitting	Vent (mm)	250 Hz	500 Hz	1000 Hz	2000 Hz	3000 Hz	4000 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	3000 Hz	4000 Hz
900	64	R,BTE	2	20	35	25	25	35	55	40	35	30	45	40	65
901	69	B,ITE	3	30	30	35	50	50	55	25	20	25	50	50	55
902	72	B,BTE	2.5	45	30	25	40	50	70	30	25	30	35	50	65
903	52	B,BTE	3	35	35	45	60	45	55	35	40	45	60	50	50
904	83	B,BTE	1	40	40	35	50	65	75	45	30	35	60	55	70
905	70	B,ITE	3	30	30	25	40	55	60	25	20	35	40	60	60
906	77	B,BTE	3	5	10	30	60	65	65	10	15	35	60	60	80
907	76	B,ITE	2.5	15	35	25	30	55	65	15	30	25	20	55	60
908	64	B,BTE	1.5	45	55	65	65		65	40	50	55	65		65
909	56	B,BTE	1.5	45	50	45	55	55	60	40	45	45	50	55	60
911	81	B,ITE	1.5	20	40	50	60	55	60	15	45	55	60	50	60

913	78	B,BTE	2	70	70	60	60	45	55	50	60	50	60	50	50
914	76	R,BTE	3	30	30	30	40	60	75	25	25	35	40	60	80
916	77	B,ITE	1.5	45	40	40	70	65	75	45	35	50	65	65	70
917	76	B,BTE	3	20	15	55	75	70	75	10	20	55	70	75	70
918	39	R,BTE	2.5	50	45	45	55	40	45	40	45	45	45	40	40
919	73	R,BTE	3	35	50	60	55	60	65	25	30	40	45	55	60
920	78	L,BTE	2	35	35	55	65	55	65	25	35	60	95	90	95
921	79	B,ITE	3	20	15	15	50	55	70	25	15	20	40	60	65
922	76	B,BTE	open	25	25	25	40	60	65	20	15	25	40	55	60
923	83	B,ITE	3	25	25	35	65	70	85	20	15	30	50	60	65
924	74	L,BTE	open	10	15	20	40	35	45	10	20	20	40	45	55
925	67	R,BTE	1.5	100	90	95	100		105	30	45	45	55	55	55

Table 2: Overview of the results of the correlation analyses between preferred REIG at 250 Hz and various audiological measurements. N is number of observations, Spearman R is the correlation coefficient, and p is the p-level.

		REIG at 250 Hz	
Parameter	N	Spearman R	p
HTL at 250 Hz	22	0.07	0.77
HTL at 500 Hz	22	0.20	0.37
LFHTLavg	22	0.15	0.52
HFHTLavg	22	0.22	0.32
NL1 target at 250 Hz	22	-0.10	0.66
NL1 target at 500 Hz	22	0.14	0.54
Vent size	22	-0.19	0.41
f_{vent}	21	-0.24	0.31
$f_{amplified}$	22	-0.26	0.25
OE/i/	20	0.14	0.55

FIGURE LEGENDS

Figure 1: The average NAL-NL1 target (asterisk, fat line) and the average real-ear insertion gain curves for each of the six test schemes fitted to 23 study participants. The curves are shown shifted in relation to the x-axis for clarity. The bars show the 95% confidence intervals.

Figure 2: The relationship between the fitted vent size and a) the frequency at which the vent stops transmitting sound directly (open circles) and the frequency at which sound becomes amplified (crosses), and b) the occlusion effect when vocalizing /i/.

Figure 3: The average performance rating allocated to each test scheme across individually selected listening situations in the field. The boxes show ± one standard error, and the whiskers show ± one standard deviation.

Figure 4: The REIG preferred at 250 Hz when the directional microphone and noise reduction were enabled as a function of the preferred REIG at 250 Hz when the features were disabled.

Figure 5: The average preference scores allocated to a) the three ‘features off’ schemes, b) the three ‘features on’ schemes, and c) the preferred ‘feature off’ and ‘feature on’ schemes in a round robin paired comparison test. The boxes show ± one standard error, and the whiskers show ± one standard deviation.

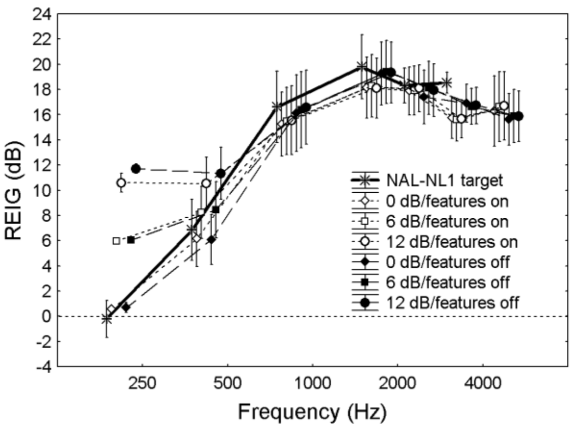
Figure 6: The average SNR required for each of four test schemes to obtain 50% correct key word score of BKB sentences by ITE and BTE wearers. The bars show the 95% confidence intervals.

Figure 7: The average left/right RMS localisation error when ignoring front/back confusions, measured for four test schemes for unilaterally and bilaterally fitted listeners. The bars show the 95% confidence intervals.

Figure 8: The average front/back RMS localisation errors when ignoring left/right confusions measured for four test schemes for ITE and BTE wearers. The bars show the 95% confidence intervals.

Figure 9: The relationship between the DI measured when directionality was on and the REIG measured on KEMAR in an anechoic chamber at 250 Hz.

Figure 10: The relationship between the preferred amount of REIG at 250 Hz when combined with the preferred condition of features on and off and the hearing threshold level at 500 Hz.



24
22
20
18
16
14
12
10
8
6
4
2
0
-2
-4
REIG (dB)
250
500
1000
2000
4000
Frequency (Hz)
NAL-NL1 target
0 dB/features on
6 dB/features on
12 dB/features on
0 dB/features off
6 dB/features off
12 dB/features off

Figure 1

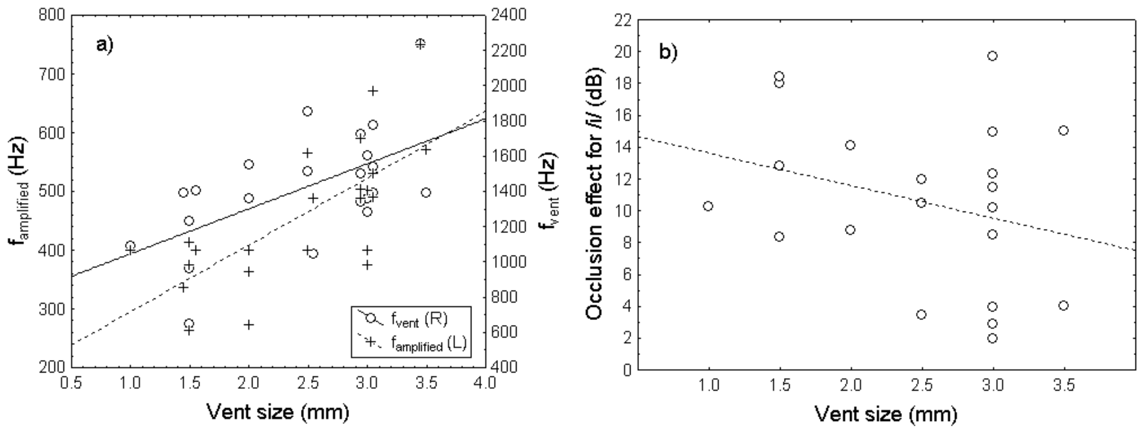

a)
f_amplified (Hz)
f_vent (Hz)
Vent size (mm)
f_vent (R)
f_amplified (L)
b)
Occlusion effect for /i/ (dB)
Vent size (mm)

Figure 2

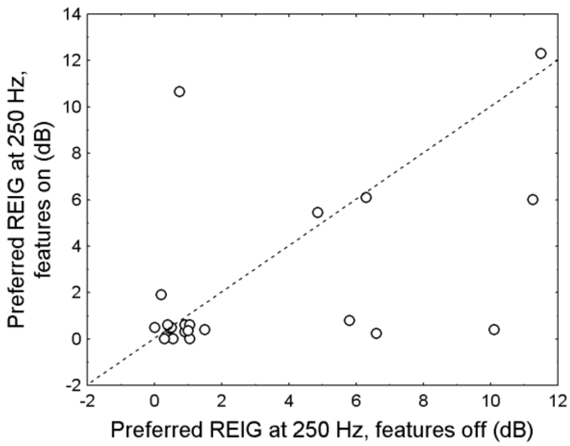
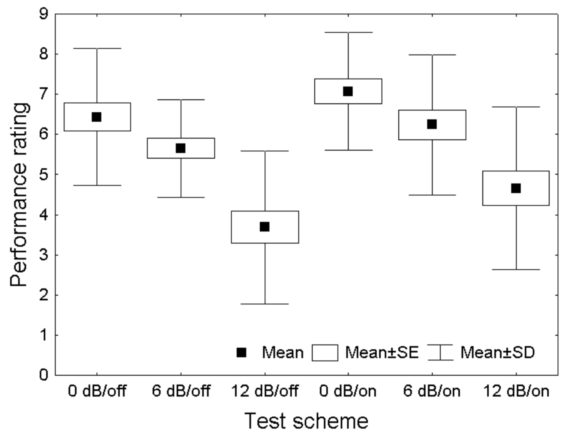
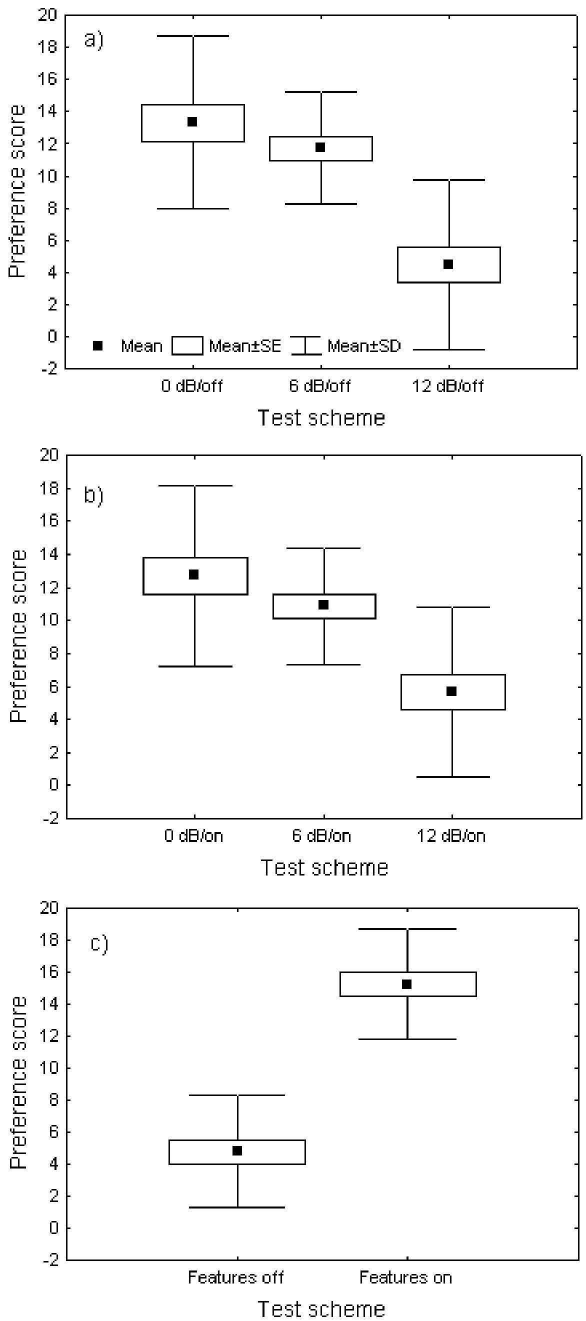

Preferred REIG at 250 Hz, features on (dB)
14
12
10
8
6
4
2
0
-2
-2
0
2
4
6
8
10
12
Preferred REIG at 250 Hz, features off (dB)

Figure 3



Performance rating
9
8
7
6
5
4
3
2
1
0
Mean
Mean±SE
Mean±SD
0 dB/off
6 dB/off
12 dB/off
0 dB/on
6 dB/on
12 dB/on
Test scheme

Figure 4



a)
b)
c)
Preference score
Test scheme
Mean
Mean±SE
Mean±SD
0 dB/off
6 dB/off
12 dB/off
0 dB/on
6 dB/on
12 dB/on
Features off
Features on
-2
0
2
4
6
8
10
12
14
16
18
20

Figure 5

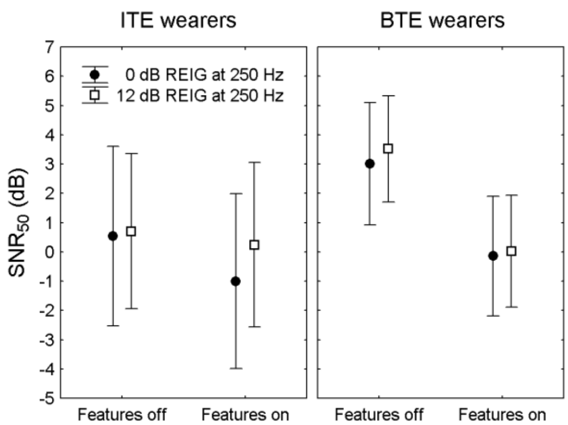

ITE wearers
BTE wearers
0 dB REIG at 250 Hz
12 dB REIG at 250 Hz
SNR50 (dB)
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
Features off
Features on
Features off
Features on

Figure 6

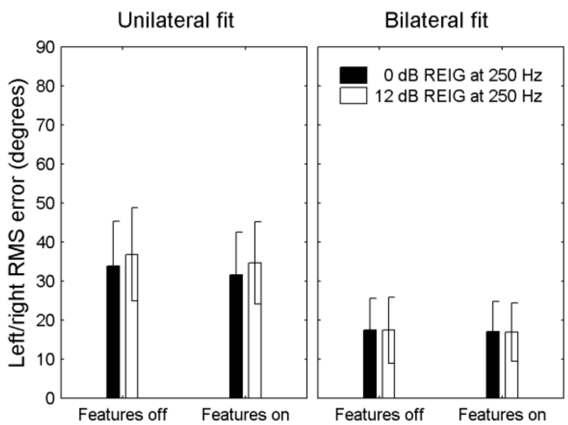

Unilateral fit
Bilateral fit
0 dB REIG at 250 Hz
12 dB REIG at 250 Hz
Left/right RMS error (degrees)
90
80
70
60
50
40
30
20
10
0
Features off
Features on
Features off
Features on

Figure 7

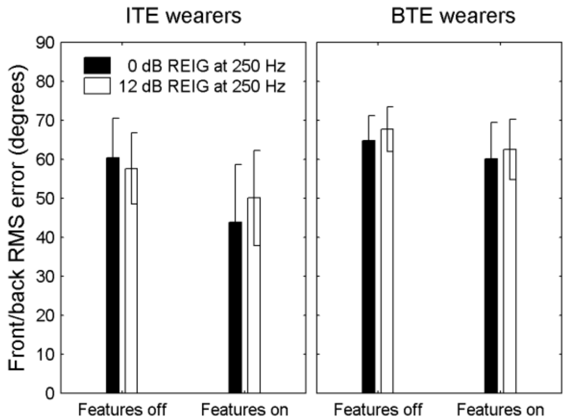
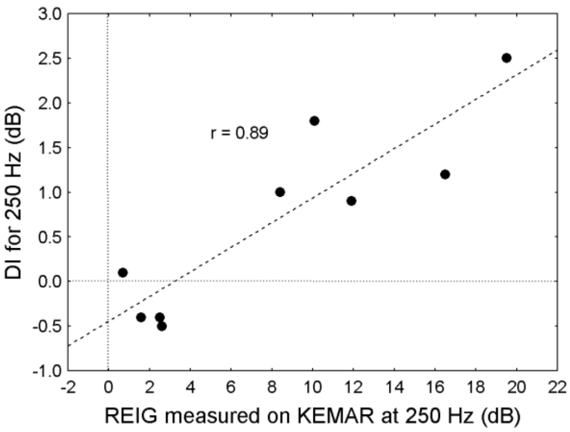

ITE wearers
BTE wearers
0 dB REIG at 250 Hz
12 dB REIG at 250 Hz
Front/back RMS error (degrees)
0
10
20
30
40
50
60
70
80
90
Features off
Features on
Features off
Features on

Figure 8



r = 0.89
DI for 250 Hz (dB)
REIG measured on KEMAR at 250 Hz (dB)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-2
0
2
4
6
8
10
12
14
16
18
20
22

Figure 9

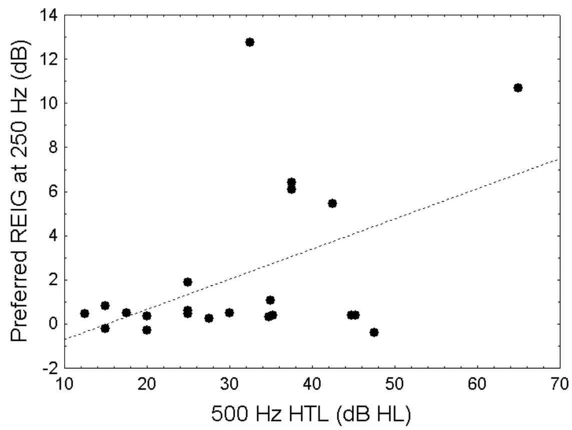

Preferred REIG at 250 Hz (dB)
500 Hz HTL (dB HL)
14
12
10
8
6
4
2
0
-2
10
20
30
40
50
60
70

Figure 10