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Comparison of three procedures for initial fitting of compression hearing aids. II. Experienced users, fitted unilaterally

Comparación de tres procedimientos para la adaptación inicial de auxiliares auditivos de compresión. II. Usuarios experimentados con adaptación unilateral

Key Words
Fitting hearing aids
Hearing impairment
Unilateral

Abstract

This paper is the second in a series comparing three procedures for the initial fitting of multichannel compression hearing aids. The first paper reported the results for a group of 10 experienced hearing aid users fitted bilaterally. This paper reports the results for a different group of 10 experienced hearing aid users fitted unilaterally. The three procedures were: (1) CAMEQ, which aims to amplify speech so as to give equal loudness per critical band over the frequency range 500–5000 Hz, and to give similar overall loudness to normal over a wide range of speech levels; (2) CAMREST, which aims to amplify speech so as to restore normal specific loudness patterns, over a wide range of speech levels; and (3) DSL [i/o], which aims to map the dynamic range of normal-hearing people into the reduced dynamic range of hearing-impaired people, with full restoration of audibility. Each subject was fitted with one Danalogic 163D digital hearing aid, using each of the three fitting procedures in turn; the order was counter-balanced across subjects. Prescribed insertion gains for 55 and 80 dB SPL input levels were verified using real-ear measurements. Immediately after fitting with a given procedure, and 1 week after fitting, the gains were adjusted, when required, by the minimum amount necessary to achieve acceptable fittings. On average, the adjustments were smallest for the CAMREST procedure, slightly larger for the CAMEQ procedure, and largest of all for DSL [i/o]. For the DSL [i/o] the gain changes were mostly negative, especially for high frequencies and the higher input level. After these gain adjustments, users wore the aids for at least 3 weeks before speech reception thresholds (SRTs) for sentences in quiet and in steady and fluctuating background noise were measured. The APHAB questionnaire was also administered. The hearing aids were then refitted with the next procedure. SRTs and APHAB scores did not differ significantly between the three procedures. We conclude that the CAMEQ and CAMREST procedures provide a more appropriate initial fitting than DSL [i/o] for unilaterally experienced hearing aid wearers. Comparison with our earlier study based on bilateral fittings suggests that the preferred gains are similar for unilateral and bilateral fittings.

Sumario

Este trabajo es el segundo de una serie en la que se comparan tres procedimientos para la adaptación inicial de auxiliares auditivos (HA) multicanal con compresión. El primer reportó los resultados de un grupo de 10 usuarios experimentados con HA en ambos oídos. Este reporta los resultados de un grupo diferente, de 10 usuarios experimentados con adaptación unilateral de HA. Los tres procedimientos fueron: (1) CAMEQ, que pretende amplificar el lenguaje de modo que proporcione una intensidad subjetiva igual por bandas críticas, en el rango de frecuencias de 500–5000 Hz, y que proporcione también una intensidad subjetiva globalmente similar en la zona de normalidad y en un amplio rango de niveles de lenguaje; (2) CAMREST, que tiende a amplificar el lenguaje de modo que se restauren patrones específicos normales de intensidad subjetiva en un amplio rango de niveles de lenguaje; (3) DSL [i/o] que pretende mapear el rango dinámico de personas normo-oyentes en el rango dinámico reducido de personas hipoacúsicas, con restauración completa de la audibilidad. A cada sujeto se le adaptó un HA digital Danalogic 163D usando los tres procedimientos de adaptación; el orden de presentación en todos los sujetos se mantuvo balanceado. Se verificaron las ganancias de inserción con niveles de ingreso de 55 y 80 dB SPL usando mediciones de oído-real. Inmediatamente después de la adaptación con un determinado procedimiento y una semana después, se ajustaron las ganancias, cuando fue necesario, con el mínimo necesario para una adaptación aceptable. En promedio, los ajustes fueron mas pequeños con el CAMREST, ligeramente mayores con CAMEQ y los mayores de todos, con DSL [i/o]. Con DSL [i/o], los cambios de ganancia fueron en su mayoría negativos, especialmente para las frecuencias agudas y los niveles de ingreso mayores. Después de los ajustes de ganancia, los sujetos usaron sus auxiliares por al menos 3 semanas antes de medir los umbrales de recepción de lenguaje (SRTs) con oraciones sin ruido y con ruido de fondo estacionario o fluctuante. También se aplicó el cuestionario APHAB. Los HA fueron entonces readaptados con el procedimiento que seguía. Las puntuaciones de SRTs y APHAB no difirieron significativamente entre los tres procedimientos. Concluimos que CAMEQ y CAMREST permiten una adaptación inicial más apropiada que el DSL [i/o] en usuarios experimentados de HA en un solo oído. La comparación con nuestros resultados anteriores basados en las adaptaciones bilaterales, sugieren que las ganancias preferidas son similares en las adaptaciones unilaterales y bilaterales.

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Introduction

In a previous study (Moore et al, 2001), we evaluated three prescriptive procedures for the initial fitting of multichannel compression hearing aids on the basis of audiometric thresholds alone. The three procedures were: (1) the Cambridge procedure for loudness equalization (CAMEQ) (Moore et al, 1999a); (2) the Cambridge procedure for loudness restoration (CAMREST) (Moore, 2000); and (3) the desired sensation level input/output procedure (DSL [i/o]) (Cornelisse et al, 1995).

The procedures are described in detail in Moore et al (2001). Here, we give only a brief summary. The CAMEQ procedure aims to place as much of the speech spectrum as possible above absolute threshold for a given overall loudness. To achieve this goal, speech frequencies between 500 and 5000 Hz are amplified so that the loudness across different frequencies is approximately equal. This is similar to the philosophy behind the NAL(R) procedure (Byrne & Dillon, 1986). In contrast, the CAMREST procedure aims to restore the normal variation in loudness between the different speech frequencies for a given overall loudness. This is more similar to the philosophy behind the FIG6 procedure, which also aims to restore loudness to normal (Killion & Fikret-Pasa, 1993). Broadly speaking, CAMEQ tends to prescribe more gain than CAMREST at medium frequencies (i.e. 1 and 2 kHz) and less gain than CAMREST at low and high frequencies. For a given hearing loss, then, CAMEQ and CAMREST produce significantly different frequency–gain characteristics, especially for low-to-medium input levels (50–65 dB). We might expect this to result in differences in preferences. The CAMEQ and CAMREST procedures are implemented in a computer program called Camfit (further information is available at http://hearing.psychol.cam.ac.uk/). In principle, the two procedures can be applied to any multichannel compression hearing aid; they are not limited to a specific aid or manufacturer. The aid can have any number of channels up to 20. The Camfit program determines the gains that should be applied in each channel, or at the standard audiometric frequencies, for sinusoids with various input levels. Gains are specified both as insertion gains and real-ear aided gains.

The DSL procedure has the goal of fitting 'the acoustic region corresponding to the extended normal auditory dynamic range into the hearing-impaired individual's residual auditory dynamic range' (Cornelisse et al, 1995). This method aims to restore the dynamic range to normal and to completely restore the audibility of speech sounds. The procedure has been widely used for paediatric hearing aid fittings (Scollie et al, 2000). We chose to include it as a comparison fitting procedure in this study, as it is also often used with adults within the UK National Health Service (NHS), although it has never been verified for this population. The procedure we used (Version 4.1) allows the audiologist to specify the type of hearing aid (e.g. behind-the-ear (BTE) or in-the-ear (ITE)), the type of ear mould used, whether the compression circuit used is of the fixed or variable compression ratio type, and the compression threshold. However, unlike the Cambridge procedures, it does not allow specification of the number of channels in a multichannel hearing aid. In principle, this is a problem, since, if the aim is to give appropriate amplification for broadband sounds such as speech, the number and width of the channels should be taken into account when recommending gains measured using other test signals, such as sinusoids or narrow bands of noise (Moore et al, 1999a; Moore, 2000).

In the study of Moore et al (2001), 10 experienced hearing aid users were fitted bilaterally with digital multichannel fast-acting (20-ms attack time and 60-ms release times) compression hearing aids, using each of the three fitting procedures described above. The order of the procedures was counter-balanced to control for test order effects. After verification of the initial fitting gain parameters, using real-ear measures, gains were adjusted, where necessary, so that loud sounds (75–80 dB SPL input level) were not uncomfortable, soft speech (60 dB SPL input level) was audible, and the sound quality was acceptable. The subjects then wore the hearing aids in everyday life for a period of about 1 week before returning for further gain adjustments, if required. All gain adjustments were recorded. They then used the hearing aids through most waking hours, for a period of not less than 3 weeks. At the end of the 3-week period, objective measures of speech recognition were obtained for speech in quiet and for speech in noise. The speech stimuli were lists of everyday sentences, and the speech-shaped noise was either constant in level or modulated with the envelope of a single talker, presented from the same location as the speech. For a given noise level, the level of the speech was adaptively varied in 5- or 3-dB steps, and the signal-to-noise ratio (SNR) for 50% speech intelligibility was measured. A subjective measure of user satisfaction was also obtained using the Abbreviated Profile of Hearing Aid Benefit (APHAB) (Cox & Alexander, 1995). Briefly, Moore et al (2001) found that gain adjustments were smallest for the CAMEQ and CAMREST procedures, but larger for the DSL [i/o] procedure, especially for high frequencies. There were no significant differences, however, between the three procedures on scores for the APHAB questionnaire or speech intelligibility tests.

The present study is similar to that of Moore et al (2001), but presents results for 10 experienced hearing aid wearers fitted unilaterally, i.e. with only one hearing aid, in the ear of choice; in the study of Moore et al, the subjects were fitted bilaterally. This study is of practical interest for two reasons. First, it is common practice in the NHS to supply only one hearing aid, even when there is a bilateral sensorineural hearing loss. Second, some hearing-impaired people choose to be fitted with a single aid even when they have a bilateral hearing loss. Third, if there are systematic changes in the gain required for unilaterally fitted subjects, these could be incorporated relatively easily into the initial fitting procedure.

The study is also of theoretical interest, for the reasons discussed below. The two Cambridge fitting procedures, CAMEQ and CAMREST, both assume bilateral fittings, although the recommended fitting parameters will differ for the two ears when the hearing loss is asymmetrical. Both procedures aim to give the same *overall* loudness for the bilaterally aided hearing-impaired person as for an average normal-hearing person listening unaided, for speech stimuli covering a wide range of sound levels. (However, only CAMREST aims to restore the loudness of different frequency bands to 'normal'.) It is commonly assumed that the overall loudness (in sones) for binaural presentation is simply equal to the sum of the loudnesses that would occur if each ear were stimulated separately (Marks, 1978; Moore et al, 1997). Thus, if a sound is presented diotically to a person with normal hearing, the loudness is assumed to be double that evoked by the same sound presented monaurally. This is consistent with much empirical data (Fletcher & Munson, 1933, 1937; Hellman & Zwislocki, 1963; Marks, 1978; Chouard, 1997), although some studies have suggested that diotic presentation leads to a loudness that is slightly less than double that for monaural presentation (Scharf & Fishken, 1970). For mid-range sound levels (40–80 dB SPL), a doubling of loudness is produced by a change in level of 6–10 dB for people with normal hearing (Stevens, 1957; Warren, 1970; Hellman, 1976; Moore & Glasberg, 1997; Zwicker & Fastl, 1999), so the effect of loudness summation across ears is reasonably large.

If loudness does sum across ears, one might expect that fitting procedures based on the assumption of bilateral fittings would lead to a loudness that was too low for a patient fitted unilaterally, since the unaided ear would contribute less than the aided ear to the overall loudness percept, except perhaps for high input sound levels (greater than 90 dB SPL), at which recruitment was complete or near complete. For low input sound levels (e.g. less than 40 dB SPL), the unaided ear might make very little contribution to loudness, so the loudness might be roughly one-half of that obtained for a binaural fitting. If this were the case, patients fitted unilaterally might prefer more gain than patients fitted bilaterally, especially for low input sound levels. The present study aims to assess whether this is the case.

Method

Aid type

All subjects were fitted with one Danalogic 163D digital BTE hearing aid. Hard acrylic skeleton ear moulds, fitted with 4-mm Libby horns (Libby, 1981), were made for most subjects, with either 1- or 2-mm vents; in some cases, it was necessary to make soft silicone ear moulds without vents, in order to control acoustical feedback problems. The 163D incorporates fast-acting compression (20-ms attack time and 60-ms release time) acting independently in 14 overlapping bands. The crossover frequencies between the bands are fixed and the compression thresholds are set by software according to the specified hearing loss. The manufacturer's software for programming the aid allows insertion gains (IGs) to be adjusted for input levels of 55 dB SPL and 80 dB SPL for centre frequencies of 0.25, 0.5, 1, 2, 4 and 6 kHz.

Subjects

Ten subjects with mild-to-severe sloping bilateral sensorineural hearing loss were tested. All were experienced hearing aid users (at least 2 years of previous hearing aid use), and had air–bone gaps in audiometric thresholds of less than 10 dB. Six of the 10 subjects had previously worn NHS analog linear hearing aids (BE 18, BE 34 and BE 102), and the remaining four subjects wore analog compression hearing aids that they had purchased in the private sector (Resound BT2 and Philips M47). Four of the 10 subjects had previously worn two hearing aids. No dead regions were identified for the subjects tested (Moore et al, 2000). The mean audiometric thresholds of the fitted ears, with associated standard deviations (SDs), are plotted in Figure 1. The ages of the subjects ranged from 45 to 85 years, with a mean of 71 years and an SD of 11.5 years.

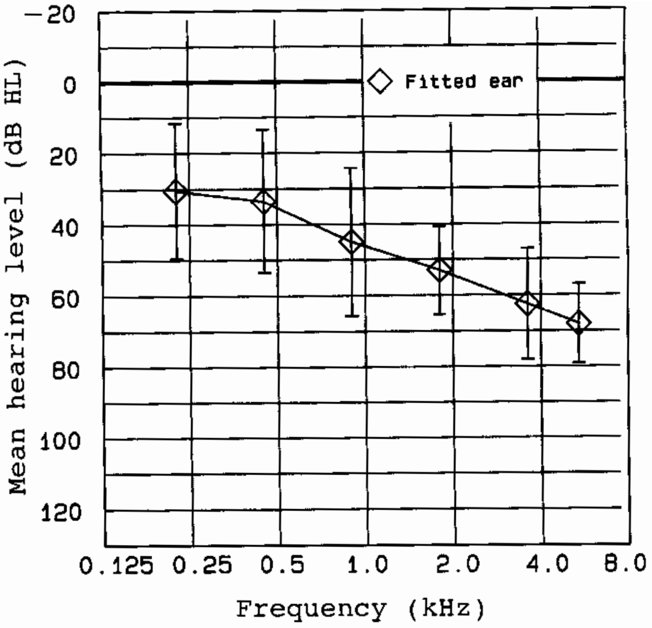

Figure 1. Means and standard deviations (SDs) of the audiometric thresholds for the fitted ear of the 10 subjects.

Experimental design

Each subject was fitted with one hearing aid, programmed according to one of the three initial fitting procedures. The order of use of the procedures was counter-balanced across subjects. For each fitting procedure, the subject used the aids in everyday life for a period of at least 4 weeks, before switching to aids fitted according to the next procedure.

To program the 163D hearing aid, two sets of six target IGs were required, one set for a low-level (55 dB SPL) input (G55), and one set for a high-level (80 dB SPL) input (G80). The CAMEQ and CAMREST fitting procedures were used to calculate the target IGs appropriate for a given hearing loss, and these were then programmed into the aids using the manufacturer's fitting software. The DSL [i/o] procedure does not provide IGs, but only real-ear aided gains (REAGs). Therefore, in order to calculate the IGs necessary to program the hearing aid, we determined the real-ear unaided response (REUR) used by the DSL procedure by entering an audiogram with 0 dB HL across the audiometric frequencies. The obtained REAGs (in dB) were 0, 2, 3, 3, 5, 12, 15, 14 and 8 for frequencies of 0.25, 0.5, 0.75, 1.0, 1.5, 2.0, 3.0, 4.0 and 6.0 kHz, respectively. The REAG values varied by less than 1 dB for input levels of 50, 65 and 80 dB. We assumed that the DSL procedure would give 0-dB insertion gain for a 0-dB hearing loss, so the REUR values are the same as the REAGs above.

All fittings were verified by measuring real-ear gains, using a Rastronics Portarem 2000 system. Where necessary, the nominal gains in the manufacturer's software were adjusted so as to achieve the target gains within a range of ±3 dB, over the frequency range between 250 Hz and 6 kHz. These adjustments were made using sinusoidal signals.

Directly following the initial fitting, checks were made that the loudness and quality (tonal balance) of speech and music stimuli were acceptable. We employed a double-blind procedure whereby neither the person fitting the hearing aid and conducting the tests, nor the hearing aid wearer, was aware of the identity of the fitting procedure being used at any time. The speech stimuli were recorded samples of male and female talkers speaking with normal and raised effort and presented at levels of approximately 60 and 80 dB SPL, respectively. The music was a piece of jazz with piano, double bass and drums, presented at about 75 dB SPL. Our goal was to perform the minimum fine-tuning necessary to make the aids acceptable to the subjects. Changes to the fitting were made only if the subject reported that some sounds were uncomfortably loud or too quiet, or that some sounds had an unnatural quality. The following rules were followed when performing the fine-tuning:

1. If all sounds were judged too loud, G55 and G80 were reduced in all frequency bands.
2. If low-level speech was judged as loud, G55 was reduced at all centre frequencies.
3. If high-level speech only was judged as too loud, G80 was reduced at all centre frequencies.
4. If the subject's own voice sounded too loud or too boomy, G80 was reduced for the frequency bands centred at 0.25, 0.5 and 1 kHz.
5. If the sound quality of speech and music was judged as dull, muffled or boomy, G55 and G80 were reduced for the frequency bands centred at 0.25, 0.5 and 1 kHz.
6. If the sound quality of speech and music was judged as too bright or tinny, G55 and G80 were increased for the frequency bands centred at 0.25, 0.5 and 1 kHz and/or G55 and G80 were decreased for the frequency bands centred at 2, 4 and 6 kHz.
7. If sounds were judged as echoing or reverberant, G55 was reduced for the frequency bands centred at 0.25, 0.5 and 1 kHz.

Subjects were also asked to give their subjective impression of the intelligibility of the speech presented in quiet and in background noise. If they reported that intelligibility was poor, the following adjustments were made:

1. If speech in quiet was judged as having low intelligibility, G55 was increased for the frequency bands centred at 2, 4 and 6 kHz.
2. If speech in noise was judged as having low intelligibility, G55 and G80 were increased for the frequency bands centred at 2, 4 and 6 kHz and decreased for the frequency bands centred at 0.25, 0.5 and 1 kHz.

In a few cases, especially when fitting with the DSL [i/o] procedure, it was necessary to reduce the gain at high frequencies for the 55-dB input level, to prevent acoustical feedback. It is possible that this had an effect on the subsequent objective and subjective measures taken, although it is not possible to say whether this was beneficial or deleterious.

Subjects were then asked to wear the hearing aid for 1 week, after which they returned to the laboratory, when further adjustments were made if requested, based on experiences with the aids during that week, as specified in the COSI questionnaire (Dillon & Ginis, 1997). Sometimes, subjects made complaints about specific sounds. The following additional adjustments were made on the basis of these complaints:

1. If the sound of crockery (a cup being banged on a saucer or a knife dropped on a plate) was unpleasant, the values of G55 and G80 were reduced at 1 and 2 kHz.
2. If the sounds of paper rustling or running water were too obtrusive, G55 and G80 were reduced at 1, 2 and 4 kHz.
3. If subjects complained of crackling sounds, produced especially by bird song, G55 and G80 were reduced at 4 and 6 kHz.

Again, the changes made were the smallest necessary to achieve a satisfactory fit. Following the final fine-tuning, each subject wore the hearing aid for at least three further weeks using the adjusted fitting, and the other measures (described below) were obtained at the end of that period. The subject was then switched to the next initial fitting procedure (according to the counter-balanced order), and the whole process was repeated.

Outcome measures

The difference between the adjusted gains and the initial target gains gives one measure of the adequacy of the initial fit for each procedure. We also used a subjective measure of user satisfaction and objective speech intelligibility measures, as follows.

THE ABBREVIATED PROFILE OF HEARING AID BENEFIT (APHAB) QUESTIONNAIRE (Cox & Alexander, 1995)

This requires subjects to rate how often they have problems in specific situations, such as 'Unexpected sounds, like a smoke detector or alarm bell are uncomfortable' or 'When I am having a quiet conversation with a friend, I have difficulty understanding.' Response alternatives range from 'Always (99%)' to 'Never (1%)'. Subjects were told that if they had not encountered a specific situation, then they should try to think of a similar situation, and if this was not possible, then not give a response for that situation. Scores are presented as the percentage of problems. Hence, low percentages indicate good performance. The results are grouped into four subscales: ease of communication (EC), understanding in reverberant environments (RV), understanding in background noise (BN), and aversiveness of sounds (AV). A mean score is also given. If subjects had been given a second program including noise reduction and/or a directional microphone, they were specifically asked to give their responses to the APHAB test on the basis of their experience with program 1, which did not include these features.

SPEECH RECEPTION THRESHOLDS (SRTs) FOR SENTENCES PRESENTED IN QUIET

Stimuli were replayed from a DAT player or CD player and presented via a QUAD amplifier and a Monitor Audio MA4 loudspeaker in a double-walled sound-attenuating booth. The subject was seated facing the loudspeaker at a distance of about 1 m. The ASL sentence lists were used (MacLeod & Summerfield, 1990). SRTs were measured using an adaptive procedure. The speech level was initially set well above the estimated SRT. Each sentence contained three key words. If the subject scored two or more key words correct, the level of the speech was decreased by 5 dB. If the subject scored less than two key words correct, the speech level was increased by 5 dB. After two turnpoints, the step size was decreased to 3 dB. The level of the speech was controlled by the tester using a Tucker-Davis Technologies PA4 attenuator. Testing continued until a complete sentence list had been presented. Probit analysis (Finney, 1971) was then conducted to determine the SRT (defined as the 50% correct point on the psychometric function).

SRTS FOR ASL SENTENCES PRESENTED IN STEADY NOISE WITH A LEVEL OF 60 AND 75 dB SPL

The noise had the same long-term average spectrum as the ASL sentences and was replayed from a DAT or CD via the same amplifier and loudspeaker as the sentences. Once again, subjects were seated directly in front of the speaker, which was placed about 1 m away. The SRTs were measured using a similar procedure to that described above. The starting level of the speech was 5 dB above the level of the noise.

SRTS FOR ASL SENTENCES PRESENTED IN NOISE MODULATED WITH THE ENVELOPE OF A SINGLE TALKER, WITH A LEVEL OF 60 AND 75 dB SPL

A similar noise has been used previously by Peters et al (1998) and by Moore et al (1999b). The detailed characteristics of the noise are described in Peters et al (1998).

Results

Comparison of insertion gains across procedures

Figure 2 shows the mean target IGs for the low-level input (G55) and high-level input (G80) for the three fitting procedures. As expected from the configuration of the hearing losses, the target gains are small for low frequencies and greater at middle to high frequencies. This is the case for all three fitting procedures. The highest target gains occur for the DSL [i/o] procedure at high frequencies.

Figure 3 shows the IGs following the fine-tuning adjustments. As expected, the gains were more similar across procedures after adjustment than before. However, consistent with our policy of making the smallest possible gain adjustments when fine-tuning, some differences did remain. Specifically, for the CAMEQ and CAMREST procedures, the IGs in Figure 3 are very similar to those shown in Figure 2, suggesting that only small changes were necessary on average in order to achieve satisfactory fits. This is not true of the DSL [i/o] procedure, where IGs for the high frequencies often had to be decreased. This was either because subjects complained of unnaturally tinny-sounding speech and/or music, or in order to control acoustical feedback problems; the latter was not usually a problem, due to the generally effective feedback suppression system on the Danalogic hearing aid. A three-way within-subjects ANOVA was conducted on the IGs resulting after the fine-tuning procedure, in order to determine whether there were significant differences remaining in the gains of the three fitting procedures. The factors were procedure (CAMEQ, CAMREST or DSL [i/o]), input level (55 or 80 dB SPL) and centre frequency (0.25, 0.5, 1.0, 2.0, 4.0 and 6.0 kHz). Although the main effect of procedure was not significant at the 0.05 probability level, there was a significant interaction of procedure and frequency ($F(10,90) = 3.46$, $p < 0.001$). Post hoc tests, based on the least significant difference test, showed that IGs for

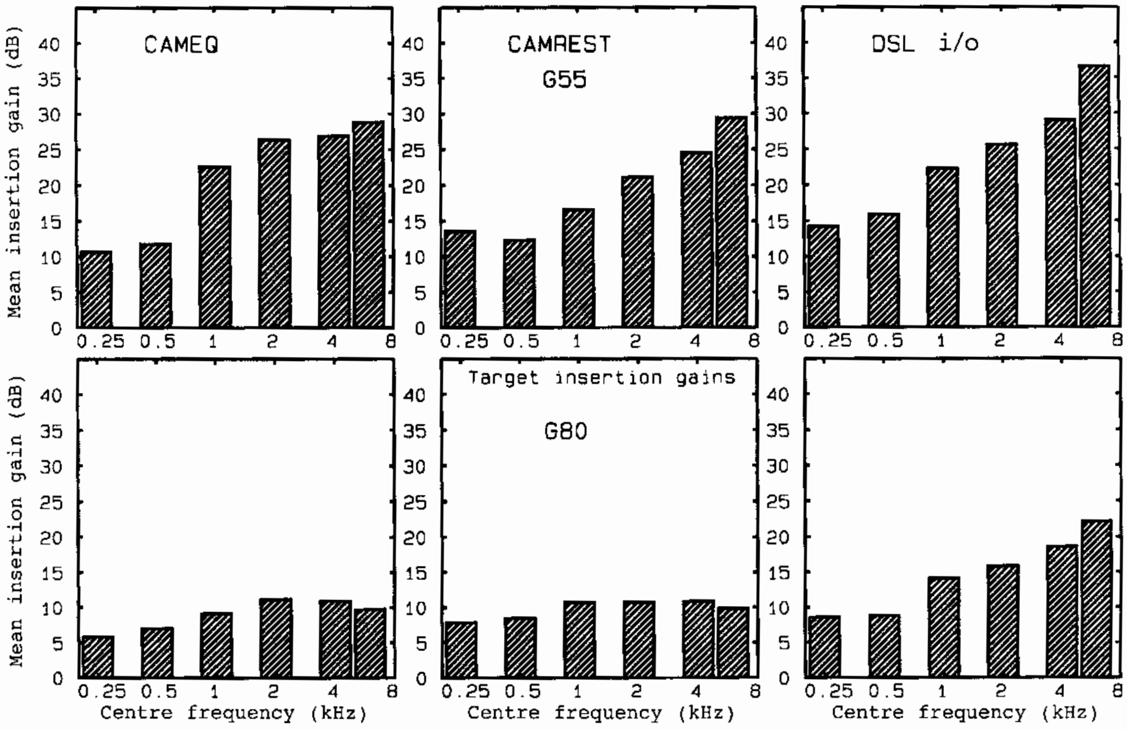

Figure 2. Mean target insertion gains recommended by the three procedures at six centre frequencies, for input levels of 55 dB SPL (top) and 80 dB SPL (bottom).

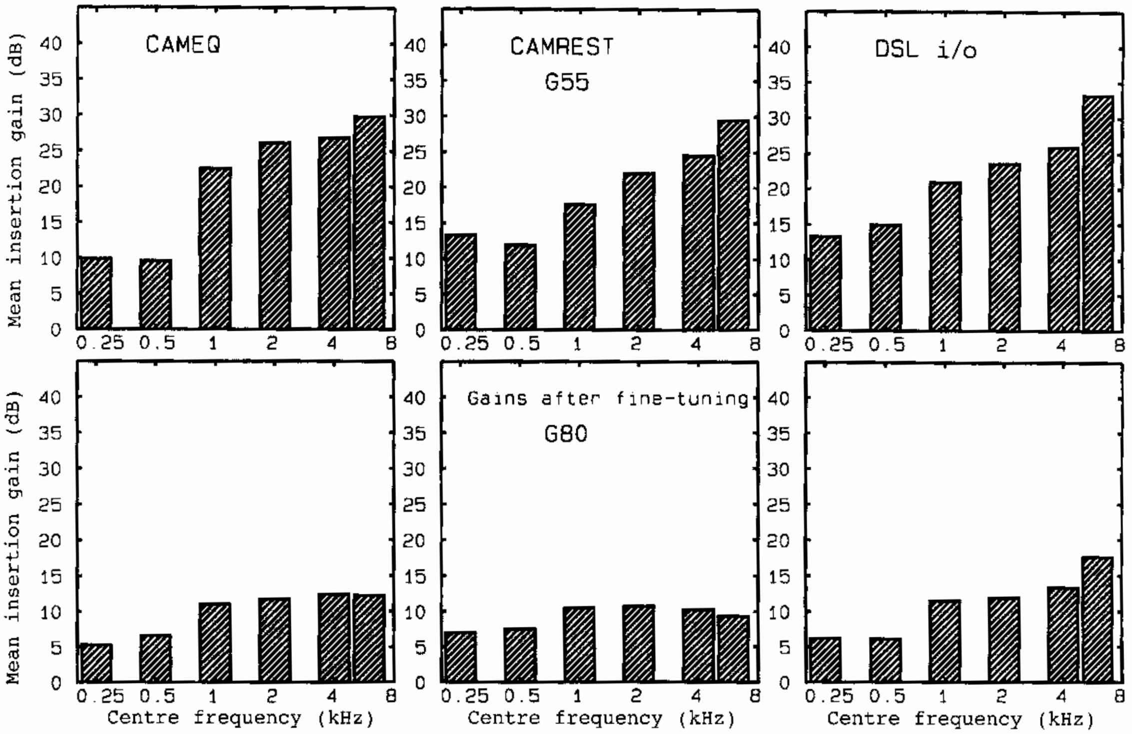

Figure 3. Mean insertion gains after fine-tuning for each of the three procedures.

CAMREST were greater than for CAMEQ and DSL [i/o] at 0.25 and 0.5 kHz. In contrast, IGs for CAMEQ were greater than for CAMREST at 2 kHz. Finally, IGs for DSL [i/o] were greater than for CAMEQ and CAMREST at 6.0 kHz. It is clear that significant differences in gain across the procedures remained after fine-tuning.

The extent to which gain adjustments were required for each procedure is illustrated in Figure 4, which shows the mean gain deviations between the target IGs and the gains after fine-tuning. The smaller these deviations, the more appropriate are the initial fits. Error bars show ±1 SD across subjects. The gain deviations for both CAMEQ and CAMREST are very small at all frequencies and for both low and high input levels. This indicates that, on average, both procedures produce initial fittings that do not systematically deviate from preferred fittings. The SDs for the CAMEQ procedure range from 1.3 to 5.2 dB (mean 3.3 dB). The SDs for the CAMREST procedure are even smaller, ranging from 1.3 to 3.1 dB (mean 2.2 dB). The variability across subjects is therefore quite small for the CAMEQ and CAMREST procedures. There is a slight tendency for the gains for the CAMREST procedure to be increased following adjustment for mid-range frequencies at low levels. This is consistent with the fact that CAMREST prescribes less mid-frequency low-level gain than the other two procedures. The gain deviations for DSL [i/o] tend to be negative, especially at high frequencies, and more so at the 80 dB SPL input level. This indicates that, on average, the gains prescribed by DSL [i/o] at high frequencies are greater than the preferred gains (although a small part of this effect can be attributed to the need to reduce high-frequency gains to reduce feedback with DSL [i/o]; this occurred in four of 10 subjects). The SDs for DSL [i/o] are larger than those for CAMEQ and CAMREST, ranging from 1.3 to 7.1 dB (mean 3.8 dB).

A three-way within-subjects analysis of variance (ANOVA) was carried out on the gain deviation measures to determine the statistical significance of differences in mean gain adjustments across procedures. The factors were fitting procedure (CAMEQ, CAMREST or DSL [i/o]), input level (55 or 80 dB SPL) and centre frequency (0.25, 0.5, 1.0, 2.0, 4.0 and 6.0 kHz). The main effect of procedure was highly significant ($F(2,18)=8.03$, $p<0.01$). Post hoc tests, based on the least significant difference test, showed that the mean gain change for DSL [i/o] (–2.8 dB) was significantly different from that for CAMEQ (0.3 dB) or CAMREST (–0.1 dB) ($p<0.05$). The mean gain change did not differ significantly between the latter two procedures. The main effects of input level and frequency were not significant ($F(1,9)=0.58$, and $F(5,45)=1.02$, respectively). However, there was a significant interaction of procedure and frequency ($F(10,90)=3.04$, $p<0.01$). Post hoc tests showed that the values of the gain changes for DSL [i/o] were significantly greater (more negative) than those for CAMEQ and CAMREST for centre frequencies of 1, 2, 4 and 6 kHz ($p<0.05$).

The mean gain change for a given procedure indicates whether the overall gain prescribed by that procedure is systematically too low or too high, but does not indicate whether the frequency-response shape is appropriate. For example, a procedure might prescribe too little low-frequency gain and too much high-frequency gain, but the gain adjustments needed to produce a satisfactory fit, when averaged across frequency, might be close to zero. Hence, a second ANOVA was conducted

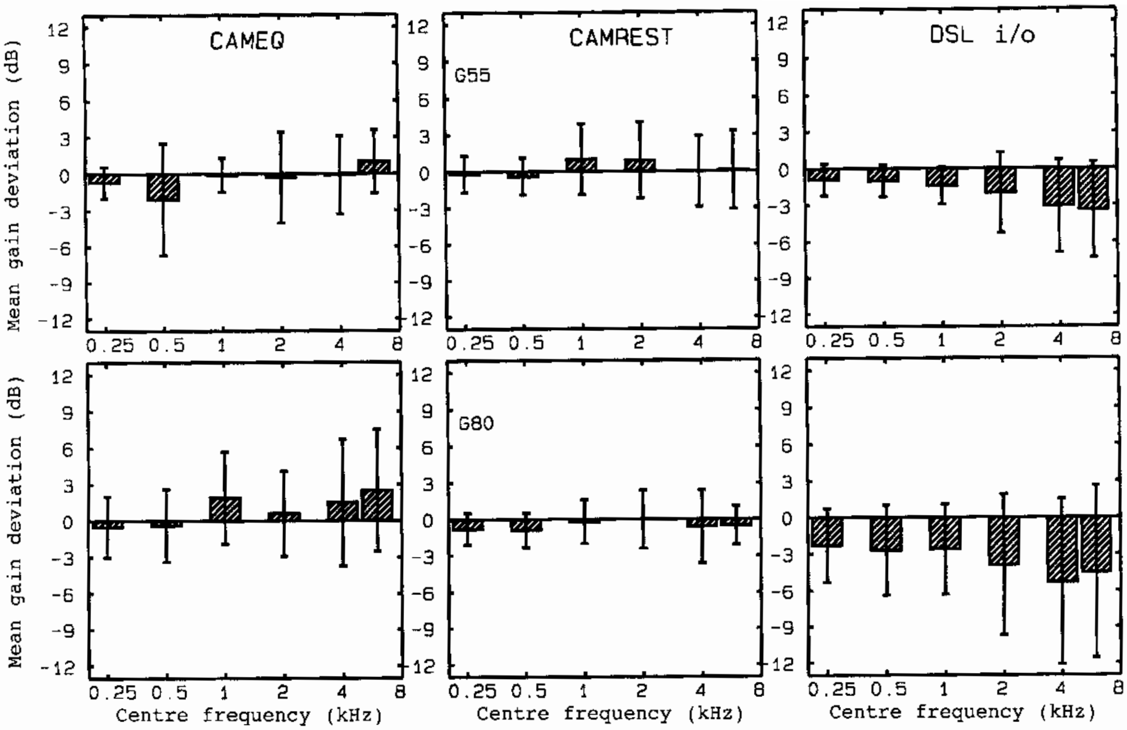

Figure 4. Mean changes in gain as a result of the fine-tuning for each of the three procedures. Error bars show ±1 SD across subjects.

on the absolute values of the gain changes, with the same factors as above. This ANOVA did not give a significant main effect of procedure ($F(2,18)=0.98$, $p=0.393$), although the mean of the absolute values of the gain changes was larger for DSL [i/o] (2.8 dB) than for CAMEQ (1.9 dB) or CAMREST (1.3 dB). There was a significant effect of centre frequency ($F(5,45)=5.67$, $p<0.01$). Post hoc tests showed that this was due to larger changes occurring at 2, 4 and 6 kHz ($p<0.05$). The main effect of input level was also found to be significant ($F(1,9)=5.63$, $p<0.05$). Post hoc tests showed that absolute gain changes were greater for the 80-dB input level than for the 55-dB input level. The interaction of procedure and frequency was not significant ($F(10,90)=1.17$, $p=0.323$).

As the 'fine-tuning' actually involved the smallest adjustments necessary to achieve acceptable fits, it could be argued that the optimal fit might not have been achieved for any one procedure. Therefore, to make a fairer comparison across procedures, we calculated the mean adjusted gains across procedures for each subject, i.e. the mean gains after fine-tuning. These might be more representative of the preferred gains. We then determined the deviation of these preferred gains from the initial target gains prescribed by each procedure. The results are shown in Figure 5. The general pattern of the results is similar to that shown in Figure 4, but the deviations are, in general, greater. The mean gain deviations for CAMEQ and CAMREST are close to 0 dB and are never greater than 4 dB. In other words, there is no systematic trend for the gain deviations to be positive or negative for the CAMEQ or CAMREST procedures. For DSL [i/o], the mean gain deviations are all negative, and they exceed 8 dB at 6 kHz for the 80 dB SPL input level. Again, these results indicate that DSL [i/o] prescribes too much high-frequency gain, especially at high input levels.

To assess the statistical significance of the gain deviations presented in Figure 5, a three-way within-subjects ANOVA was performed with the factors input level, centre frequency and fitting procedure. The main effect of procedure was significant ($F(2,18)=7.16$, $p<0.01$). Post hoc tests showed that the mean gain change for DSL [i/o] (–2.7 dB) was significantly different from that for CAMEQ (0.3 dB) or CAMREST (–0.2 dB) ($p<0.05$), although the latter two did not differ significantly. There was a significant interaction of procedure and frequency ($F(10,90)=5.08$, $p<0.01$). Post hoc tests showed that the values of the gain changes for DSL [i/o] were significantly greater (more negative) than those for CAMEQ and CAMREST for centre frequencies of 4 and 6 kHz ($p<0.05$). There was also a significant interaction of procedure and level ($F(2,18)=22.94$, $p<0.01$). Post hoc tests showed that the values of the gain changes were greater at the higher level than at the lower level for DSL [i/o] ($p<0.05$) but were not significantly different for the two levels for CAMEQ and CAMREST.

A three-way within-subjects ANOVA was conducted on the absolute values of the gain changes shown in Figure 5. The main effect of procedure was not found to be statistically significant ($F(2,18)=1.07$, $p=0.36$). There was a significant interaction of procedure and input level ($F(5,45)=5.46$, $p<0.01$). Post hoc tests showed that the values of the gain changes were greater at the higher level than at the lower level for DSL [i/o] ($p<0.05$) but were not significantly different for the two levels for CAMEQ and CAMREST. The interaction of procedure and frequency was not statistically significant ($F(10,90)=2.11$, $p=0.11$).

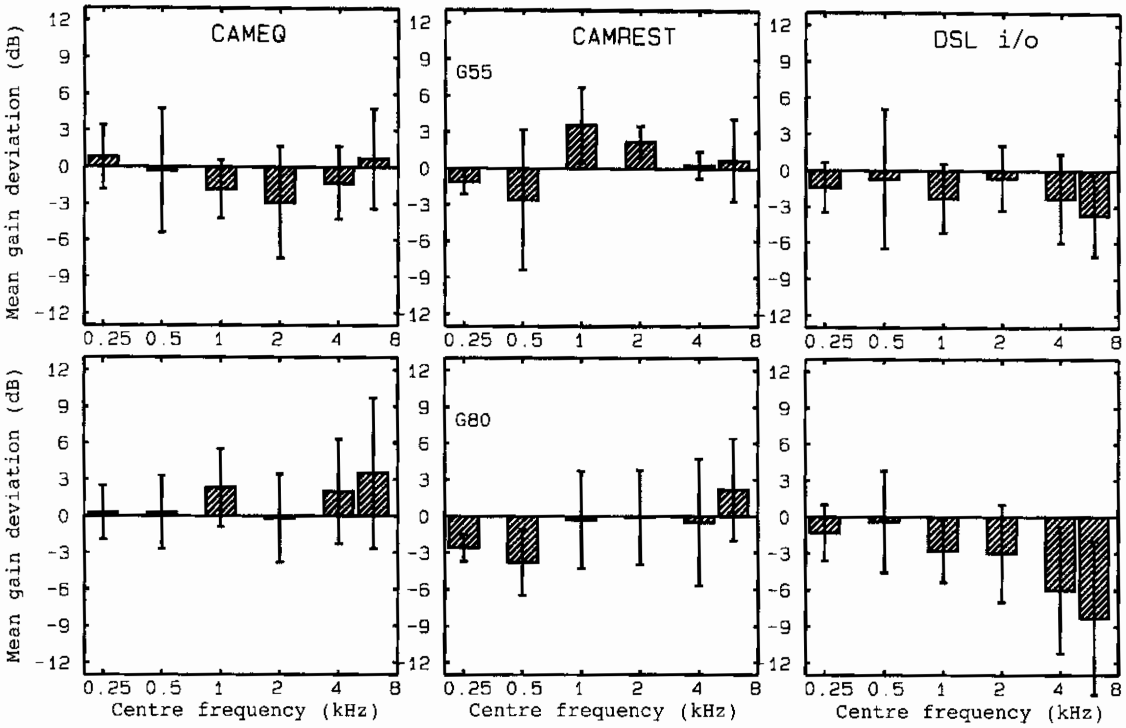

Figure 5. Mean differences between the initial target gains recommended by each procedure and the gains after fine-tuning, taking the latter measure as the average across the three procedures. Error bars show ±1 SD across subjects.

Results of the APHAB

Figure 6 shows the mean percentage problem scores for the APHAB questionnaire. Scores are shown for each of the four subscales (EC, RV, BN and AV), as well as the overall mean, for each of the three fitting procedures. Error bars show ±1 SD. The percentage of problems was similar for the three procedures, and mean scores were almost identical. A two-way within-subjects ANOVA with factors procedure and subscale showed no significant effect of procedure ($F(2,18)=0.74$, $p=0.49$), and no significant interaction of procedure and subscale ($F(6,54)=0.95$, $p=0.46$). There was, however, a significant effect of subscale ($F(3,27)=3.06$, $p<0.05$). Post hoc tests indicated that this was due to the lower percentage of problems reported for the EC subscale, for all three procedures. The similarity in scores for the three procedures is not surprising when one considers that the effect of the fine-tuning was inevitably to make the fittings for the three procedures more similar to each other.

Results of the SRT measurements

Figure 7 shows the mean results of the SRT measurements. Error bars show ±1 SD. As for the APHAB questionnaire, the SRTs were also obtained *after* adjustment of the gains to achieve acceptable fits.

The SRTs in noise are shown by the four sets of bars on the left-hand side of Figure 7, and should be referred to the left-hand ordinate. They are plotted as SNRs, with more negative values (indicating better performance) at the top. Although there were differences in the SRTs for the different noise conditions and levels, the SRTs did not differ markedly across procedures. This is not surprising, as in all cases the speech was amplified so as to be above absolute threshold. There were only small differences in gain, frequency response and compression ratio for the different fitting procedures, and previous research has shown that these factors have little effect on the intelligibility of speech in noise, when audibility is taken into account (van Buuren et al, 1995, 1999). A three-way within-subjects ANOVA with the factors procedure, noise level and noise type (steady or modulated) showed that the main effect of procedure was not significant ($F(2,18)=0.1$, $p=0.9$). The effect of noise level was significant ($F(1,9)=12.44$, $p<0.01$), with lower SRTs being associated with the higher noise level. The effect of noise type was also significant ($F(1,9)=119.9$, $p<0.01$), with SRTs for the modulated noise being on average about 2 dB better than for the steady noise. The interaction of noise level and noise type was also significant ($F(1,9)=5.83$, $p<0.05$), as the improvement in SRTs for the higher noise level only occurred for the modulated noise, and not for the steady noise. The thick horizontal bars show means and standard deviations of SRTs measured for normal-hearing subjects aged between 41 and 62 years, using the same stimuli. The hearing-impaired subjects perform about 5 dB more poorly than the normal-hearing subjects for the steady noise background and about 8 dB more poorly for the modulated noise background. This is consistent with earlier work showing that hearing-impaired people are less able than normal-hearing people to take advantage of temporal dips in a fluctuating background sound (Carhart & Tillman, 1970; Duquesnoy, 1983; Hygge et al, 1992; Takahashi & Bacon, 1992; Eisenberg et al, 1995; Moore et al, 1995; Peters et al, 1998). Linear amplification (Peters et al, 1998) or fast-acting compression (Moore et al, 1999b) can alleviate this problem, but not eliminate it.

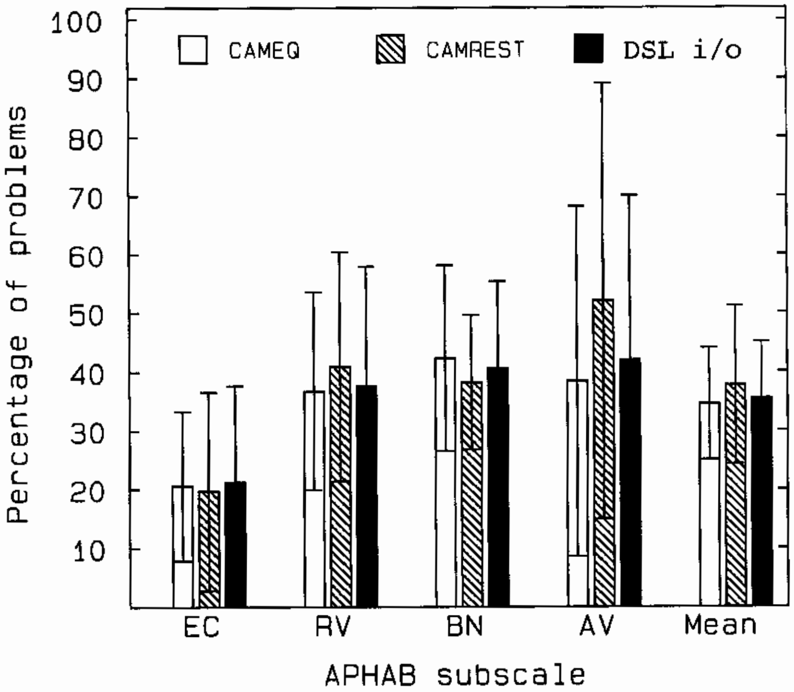

Figure 6. Mean scores for the APHAB test for each of the three fitting procedures. Error bars show ±1 SD. Scores are shown for each APHAB subscale, and for the mean. Note that these scores are based on fittings after fine-tuning, not initial fittings recommended by the three procedures. The subscales are: ease of communication (EC), listening in reverberant conditions (RV), listening in background noise (BN), and aversion to intense sounds (AV).

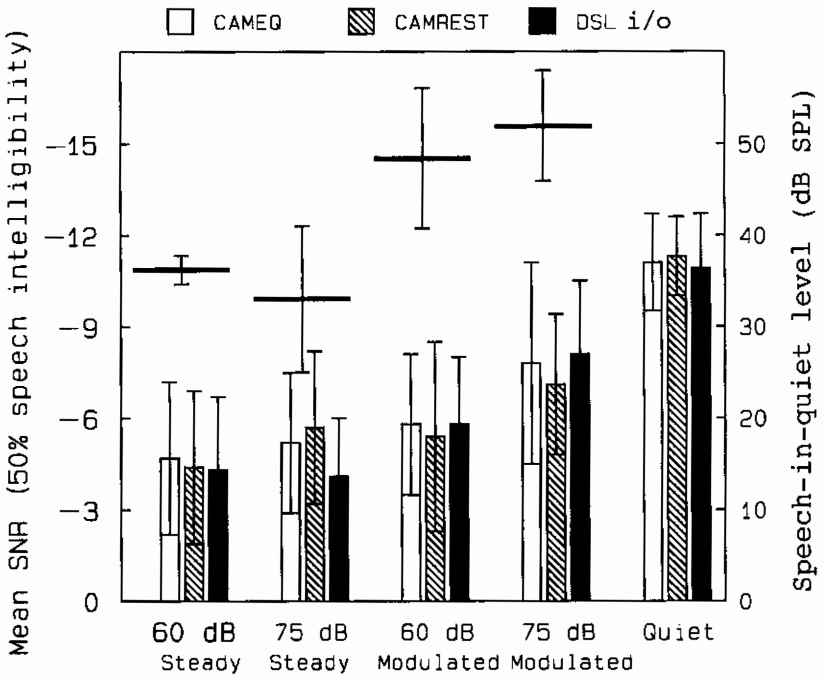

Figure 7. Mean SRTs in quiet (right-most three bars, referred to right-hand ordinate) and in steady and amplitude-modulated noise at 60 and 75 dB SPL(remaining bars, referred to left-hand ordinate), for each of the three procedures. Error bars show ±1 SD. Note that these SRTs are based on fittings after fine-tuning, not initial fittings recommended by the three procedures. The thick horizontal bars show SRTs (mean±1 SD) for normal-hearing subjects tested with the same stimuli.

Mean SRTs in quiet are shown by the three right-most bars, and should be referred to the right-hand ordinate. A one-way within-subjects ANOVA showed that there was no significant difference between SRTs in quiet for the three procedures ($F(2,18)=0.23$, $p=0.80$).

Discussion

As in the study of Moore et al (2001), we found that the most sensitive measure of the adequacy of the initial fitting parameters recommended by a given procedure was the extent to which the gains needed to be adjusted to achieve a satisfactory fitting. As for the bilaterally fitted subjects of Moore et al (2001), we found that, for our group of experienced hearing aid wearers fitted unilaterally, the CAMEQ and CAMREST procedures performed best in this respect. That is, for both procedures, only small adjustments in gain were required for the subjects to be satisfied with the fitting. Moreover, the fact that the mean adjustments were very close to zero indicates that there is little that is systematically inappropriate in the two procedures. However, this should not be taken to mean that these procedures give satisfactory initial fits for *all* hearing-impaired listeners. We believe that some fine-tuning will often be necessary, especially when one considers that the CAMEQ and CAMREST procedures were derived using a model of loudness perception (Moore & Glasberg, 1997). It is possible to take into account individual differences in loudness perception between hearing-impaired listeners with similar hearing losses, by adjusting the parameters of the loudness model. However, when it was applied to calculate the prescribed gains, only typical values were assumed. Therefore, although the prescribed gains would be expected to be suitable on average, there will always be individual cases where they are not. In these cases, fine-tuning of the hearing aid would be necessary in order to achieve a satisfactory fit. Even so, the SDs of the gain adjustments were rather small for the CAMEQ and CAMREST procedures (typically less than 3 dB), meaning that any fine-tuning required for these two procedures is likely to be small. In practice, no adjustment at all was required for five and four out of 10 subjects, for the CAMEQ and CAMREST procedures, respectively.

In contrast, the DSL [i/o] procedure required substantial adjustments for seven out of 10 subjects. Specifically, the mean gain adjustments were always negative, indicating that most listeners thought that the hearing aid made sounds too loud, especially for sounds containing high frequencies, such as bird song and running water. This is apparent in the mean value of the gain adjustments necessary at high frequencies (about 6–8 dB). It should be pointed out that, as the SDs for the DSL [i/o] gain adjustments are also quite high (about 5–6 dB), this procedure may have suited some subjects more than others. Unfortunately, the results of the current study do not allow us to identify any factors that might indicate which subjects will require more in the way of fine-tuning. We determined the correlation of factors such as configuration, degree and duration of hearing loss, age and occupation with the amount of fine-tuning necessary to achieve acceptable fits. No single factor or group of factors reliably predicted the amount of fine-tuning required.

It is disappointing that neither the objective speech intelligibility tests nor the APHAB questionnaire revealed any significant differences among the three fitting procedures. However, the fine-tuning that had to be performed to obtain satisfactory fits, especially for the DSL [i/o] procedure, resulted in more similar gains and compression ratios for the three procedures than obtained from the initial prescriptions. Thus, it is not surprising that scores on the APHAB test and the SRTs did not differ significantly across the three procedures.

On the basis of the gain adjustments performed in order to obtain satisfactory hearing aid fittings, we conclude that CAMEQ and CAMREST give more satisfactory initial fittings and require less fine-tuning than DSL [i/o].

We turn now to a comparison of our results with those of Moore et al (2001). Comparison of Figure 2 in the current study with the corresponding figure (also Figure 2) in Moore et al (2001) shows that the pattern of target IGs across frequency, input level and fitting procedure is very similar for the unilaterally fitted subjects and the bilaterally fitted subjects of Moore et al (2001). This was confirmed by the results of a four-way ANOVA, with the factors group, input level, fitting procedure and centre frequency, which showed that, although there was a significant main effect of group ($F(1,685)=25.7$, $p<0.01$), none of the interaction terms involving the group factor was statistically significant at the 0.05 level. The significant effect of group was due to mean target IGs being 3 dB lower for the unilaterally fitted group than for the bilaterally fitted group. This was due to the generally lower (i.e. better) absolute hearing thresholds of the unilaterally fitted group. Consequently, all three procedures prescribed lower gains. A very similar result was found for a comparison of the gains after fine-tuning for the unilaterally and bilaterally fitted groups (compare Figure 3 in the current study and that of Moore et al (2001)).

Comparison of Figures 4 and 5 in the current study with those of Moore et al (2001) also suggests that there was very little difference in the pattern of gain adjustments necessary to achieve a satisfactory fit for the unilaterally and bilaterally fitted groups. The results of a four-way ANOVA did not show a significant effect of group ($F(1,685)=0.22$, $p=0.64$), or of any interaction terms associated with the group factor, at the 0.05 level. In other words, the unilaterally and bilaterally fitted groups required very similar adjustments in the prescribed gains in order to achieve satisfactory fits; in the case of the CAMEQ and CAMREST procedures, the adjustments were very small for both groups. However, for the DSL [i/o] procedure, the adjustments were much larger and of a similar magnitude for both groups.

Similarly, there was no statistically significant difference between the APHAB questionnaire results for the unilaterally and bilaterally fitted groups ($F(1,216)=1.16$, $p=0.28$). Comparison of Figure 7 in the current study with that of Moore et al (2001) suggests that the bilaterally fitted group performed slightly better (about 1 dB SNR) than the unilaterally fitted group on the speech-in-noise test; this was confirmed by the presence of a significant effect of group ($F(1,225)=13.51$, $p<0.01$). This result is consistent with previous studies showing that binaural aiding usually leads to lower SRTs than monaural aiding (Laurence et al, 1983). Consistent with the results of Moore et al (2001), the unilaterally fitted subjects were able to make some use of the dips present in the modulated noise masker to improve their SRT scores. However, the improvement was less than has been reported previously for normal-hearing subjects (Hygge et al, 1992; Eisenberg et al, 1995; Moore, 1995).

As discussed in the Introduction, from consideration of the effects of loudness summation across ears, one might expect that patients fitted unilaterally with the CAMEQ or CAMREST procedures would prefer more gain than patients fitted bilaterally, especially for low input sound levels. In fact, comparison of the present results with those of Moore et al (2001) does not reveal any evidence for such an effect. The gain changes required by the subjects fitted unilaterally with the CAMEQ or CAMREST procedures were close to zero for both input sound levels (55 and 80 dB SPL), as was the case for the subjects fitted bilaterally by Moore et al (2001). This may indicate that overall loudness per se is not critical in determining satisfaction with a hearing aid fitting. It is possible that satisfaction with gains for low-level inputs is determined mainly by the audibility of weak speech sounds. In this context, it is noteworthy that absolute thresholds for detecting sounds are only slightly affected by the use of two ears versus one ear. For people with normal hearing, the monaural threshold is about 2 dB higher than the binaural threshold when sensitivity is equal at the two ears, or when sensitivity at the two ears is 'equated' by an adjustment of level in one ear (Pollack, 1948). However, when one ear is more sensitive than the other, as is often the case, the threshold when listening with two ears is often very close to the threshold for the better ear (Pollack, 1948; Fletcher & Munson, 1933).

Theoretically, differences in loudness produced by unilateral versus bilateral aiding should be smaller for high input sound levels than for low input sound levels, as the loudness in the unaided ear will often approach 'normal' values at high sound levels, as a result of loudness recruitment. Thus, it is not surprising that, for the 80-dB input level, the gain changes needed to achieve satisfactory fittings were similar for the bilateral fittings of Moore et al (2001) and the unilateral fittings of the present study. However, even for high input levels, patient satisfaction with gains may be determined partly by factors other than loudness. For example, distortion in the middle ear (Dallos, 1973; Rosowski, 1996) or inner ear (Rhode, 1977), or in the hearing aid, may increase for high input levels, and the user may prefer gains that limit this distortion to acceptable values.

Conclusions

This paper compares three procedures for the initial fitting of hearing aids with multi-band compression, unilaterally fitted to experienced users. The following are our main conclusions:

1. The adjustments of the prescribed gains required to achieve satisfactory fits were, on average, smaller for the CAMEQ and CAMREST procedures than for the DSL [i/o] procedure.
2. The mean gain adjustments were consistently negative for the DSL [i/o] procedure, indicating that the prescribed gains were, on average, greater than preferred gains, especially at high frequencies.
3. APHAB scores obtained *after* adjustment of gains to achieve acceptable fits did not differ significantly between the three procedures.
4. SRTs in noise, obtained *after* adjustment of gains to achieve acceptable fits, did not differ significantly between the three procedures.
5. SRTs in quiet did not differ significantly between the three procedures.
6. On the basis of the gain adjustments required, the CAMEQ and CAMREST procedures give a more satisfactory initial fit than the DSL [i/o] procedure for experienced adult aid users fitted unilaterally.
7. The gain adjustments required to achieve satisfactory fittings for the CAMEQ and CAMREST procedures, as found in the present study, were very similar to those obtained in our earlier study (Moore et al, 2001) using bilateral fittings; in both studies, gain adjustments were close to zero, on average. Since the unilateral fittings would have led to lower overall loudness than the bilateral fittings, at least for low input levels, this implies that loudness per se is not critical in determining patient satisfaction with low-level gains. Perhaps the audibility of weak sounds is the critical variable.

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