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Linear and nonlinear hearing aid fittings – 2. Patterns of candidature

Adaptación de auxiliares auditivos lineales y no lineales – 2. Patrones de selección de candidatos

Key Words

Compression
Candidature
Speech intelligibility
Listening comfort
Satisfaction
Audiogram
Auditory ecology
Cognitive function
Psychoacoustics

Abbreviations

AVC: automatic volume control
HTL: hearing threshold level
ISI: interstimulus interval
SNHL: sensorineural hearing loss
ULL: uncomfortable listening level
WDRC: wide dynamic range
compression

Abstract

We studied candidature for linear, slow-acting AVC hearing aids, and fast-acting WDRC hearing aids in a within-subject within-device crossover design of 50 listeners with SNHL. Candidature dimensions include HTLs, ULLs, spectro-temporal and masking abnormalities, cognitive capacity, and self-reports and acoustic measures of auditory ecology. Better performance with linear fittings is associated with flatter audiograms, wider dynamic range, and smaller differences in dynamic range between low and high frequencies, and also with more restricted auditory lifestyles. Better performance with all nonlinear fittings is associated with more sloping audiograms, more restricted dynamic ranges, greater differences in dynamic range between low and high frequencies, and more varied auditory lifestyles. Differential performance between WDRC and AVC fittings is associated with patterns of variation in auditory ecology (rapid versus slow changes) and cognitive (high versus low) capacity. Differential performance between WDRC in two channels, and a hybrid with WDRC in a low-frequency and AVC in a high-frequency channel is associated with psychoacoustic tests of cochlear function (high susceptibility to spectral and temporal smearing, and high susceptibility to upward spread of masking respectively). Patterns of candidature include measures beyond auditory function in the domains of cognitive capacity and auditory ecology.

Sumario

Estudiamos cincuenta sujetos con SNHL buscando criterios de selección para adaptar auxiliares auditivos lineales, con AVC de acción lenta, o con WDRC de acción rápida, en un diseño cruzado que juzgaba variaciones intra-sujeto y con respecto al mismo dispositivo. Los criterios bajo estudio fueron HTL y ULL, anomalías del espectro temporal y de enmascaramiento, habilidad cognitiva, y auto-reportes y medidas acústicas de ecología auditiva. Se asoció un mejor desempeño al hacer las adaptaciones lineales en sujetos con audiogramas más planos, con rangos dinámicos más amplios y con pequeñas diferencias en el rango dinámico entre frecuencias graves y agudas, así como con estilos de vida auditiva más restringidos. Un mejor desempeño en todas las adaptaciones no lineales se asoció con audiogramas con pendiente, con rangos dinámicos más restringidos, con mayores diferencias en el rango dinámico entre frecuencias graves y agudas, y con estilos auditivos de vida más variados. El desempeño diferencial entre adaptaciones con WDRC y con AVC se asoció con patrones de variación en la ecología auditiva (cambios rápidos vs. lentos), y con habilidad cognitiva (alta vs. baja). El desempeño diferencial entre WDRC en dos canales y un híbrido que utilizaba WDRC en una frecuencia baja, con un AVC en un canal de alta frecuencia se asoció con pruebas psicoacústicas de función coclear (una alta susceptibilidad a la disminución en la nitidez espectral y temporal, y alta susceptibilidad a una diseminación ascendente del enmascaramiento, respectivamente). Los patrones para selección de candidatos incluyen mediciones más allá de la función auditiva en el ámbito de la capacidad cognitiva y de la ecología auditiva.

Modern hearing aids offer great flexibility in the processing and fitting features that they employ. This has been accelerated by the move to digital technology. A companion article in this volume (Gatehouse et al, 2006) has studied the degree of benefit between linear and nonlinear frequency-gain characteristics delivered to hearing-impaired listeners at both group and individual level. It has shown that differing patterns of benefit across fittings do occur, and that those patterns themselves differ depending upon the domain of outcome (e.g. speech intelligibility compared to listening comfort). These analyses contain the implicit assumption that there are features in hearing aids which are likely to deliver benefit to listeners in general. In this article we wish to study the concept of candidature, whereby there might exist characteristics of listeners which determine the

degree and domain of benefit from any particular feature, and hence the differential benefit delivered by one feature compared to another. Thus the optimum feature set for an individual hearing-impaired listener might be a function of some set of that listener's characteristics.

At its most basic level the concept of candidature is well established, at least in terms of the implementation of a particular feature. It is universally accepted that the optimum gain of a linear hearing aid fitting will vary with hearing thresholds as a function of frequency according to some prescriptive rationale (e.g. Byrne & Dillon 1986). When studying the benefits of nonlinear amplitude compression systems compared to a linear reference, research results show the influence of audiogram slope, the residual dynamic range and the difference

in dynamic range between high and low frequencies (Lunner et al, 1997a; Lunner et al, 1997b; Moore et al, 1992).

One reason for the limited benefit to listeners from hearing aid fittings is that sensorineural hearing loss entails suprathreshold deficits in addition to raised thresholds of hearing (Plomp, 1978). These deficits include degraded frequency resolution, degraded temporal resolution, abnormal masking patterns and abnormal growth of loudness (Moore, 1998). Some amplitude compression rationales use measures of loudness growth to determine compression parameters (Cox, 1995; Kiessling, 1995; Launer et al, 1996, Launer & Moore, 2003) which can be considered a form of candidature. However there are contrary arguments that prediction from pure-tone thresholds is of comparable robustness (Elberling, 1999). In general there do not appear to be established fitting rationales which rely on the abnormal psychoacoustics accompanying sensorineural hearing loss to determine candidature for a feature or for the particular parameters of a feature, though research on cochlear dead regions suggests that psychoacoustical measures of the extent of dead regions might influence aspects of an optimal prescribed frequency-gain characteristic (Baer et al, 2002; Moore 2004; Mackersie et al, 2004).

One example supporting the concept of candidature is the finding that for children with profound hearing loss there appear to be two subpopulations, one of which gains material additional benefit from a nonlinear as opposed to a linear fitting, while the other group performs less well with the nonlinear fitting (Boothroyd et al, 1988). One potential reason for contradictory results in the literature might be that analyses are almost always conducted at the group level on the assumption that there will be features conferring benefit across listeners. Of course other characteristics of the experiments, such as limited statistical power, will also contribute.

Where the particular characteristics of hearing aid fittings are in opposition, the issue of candidature is particularly pointed. For example, the companion article to this one (Gatehouse et al, 2006) contains one fitting which implements fast-acting wide dynamic range compression in both a low-frequency and a high-frequency channel (referred to as *FAST-FAST*) and another which implements fast-acting wide dynamic range compression in a low-frequency channel and slow-acting automatic volume control in a high-frequency channel (*FAST-SLOW*). Because sensorineural hearing losses usually slope from low frequencies to high frequencies, the *FAST-FAST* fitting implements more compression in the high-frequency channel than the low, with the aim of increasing moment-to-moment audibility. In contrast, for any short-term speech segment the *FAST-SLOW* fitting leaves the high frequencies untouched and implements compression in the low-frequency channel. It seems unlikely that two rationales could both deliver incremental benefit across groups of listeners when one indicates greater compression in high as opposed to low frequencies, whilst the other indicates the opposite. The more likely scenario is that there are groups of listeners for whom a *FAST-FAST* fitting might confer incremental benefit and other groups for whom a *FAST-SLOW* fitting might be superior.

Although audibility and the abnormal psychoacoustics of sensorineural hearing loss are of definite importance in the benefit delivered by hearing aid fittings, there are undoubtedly nonauditory factors that influence the benefit that listeners

derive from amplification. There is an established literature which shows that aspects of personality, attitudes and expectations to hearing aids are material correlates of benefit (Gatehouse, 1994; Cox et al, 1999). In addition, aspects of cognitive function are implicated in the benefits that different hearing aid features confer for speech intelligibility in noise (Gatehouse et al, 1999), and also implicated in listeners' recognition of a noise-reduction feature (Lunner, 2003).

In addition to these auditory and nonauditory aspects of candidature, we suggest aspects of auditory lifestyle or ecology can be influential. By auditory ecology we refer to the range of acoustical environments and perceptual demands in those environments that different hearing-impaired listeners experience. An early demonstration of the potential importance of auditory ecology in determining the benefits of nonlinear amplitude compression systems compared to linear fittings demonstrated that listeners with more restricted auditory lifestyles are more likely to benefit from linear compared to nonlinear fittings (Gatehouse et al, 1999). Furthermore, fittings which employ fast-acting wide dynamic range compression (WDRC) stem from different conceptual bases from those featuring slow-acting automatic volume control (AVC). The former aim to improve moment-to-moment audibility within a speech signal (and hence act across short timescales), whilst the latter aim to compensate for the changes in an ongoing auditory environment, or the changes which occur as a listener moves from one environment to another (and therefore operate across longer timescales as the environments vary more slowly). Given these different conceptual bases, it is likely that candidature criteria will also differ.

This article reports on measures of candidature from each of the above domains for a within-listener crossover design of linear and nonlinear amplitude compression systems with fast and slow time constants.

Methods

Subjects, hearing aid fittings, experimental design, and outcome measures

This article forms a companion to Gatehouse et al (2006), which investigated the group and individual benefits of linear and nonlinear processing with differing time constants. It extends the previous work to study what predictive leverage may be available to identify which listeners derive which types and degrees of benefit. As such it uses the same experimental design.

Briefly, this consisted of 50 listeners with bilateral symmetric sensorineural hearing loss in a within-subject crossover design of five hearing aid fittings. Wherever practicable, block randomisation was employed, with the details of each fitting masked from both subject and experimenter. The five hearing aid fittings consisted of two linear reference conditions (one single-channel labelled *NAL-RP* and one two-channel labelled *LINEAR*), and three two-channel compression fittings with combinations of fast (40 ms) and slow (640 ms) release times in the low-frequency and high-frequency channels (labelled *SLOW-SLOW*, *FAST-FAST*, and *FAST-SLOW*). A series of self-report measures and speech tests were used to assess outcome, and were reduced to four benefit factors, labelled *Listening Comfort*, *Satisfaction*, *Reported Intelligibility*, and *Speech Test Performance*. Full details are available in Gatehouse et al (2006).

Audiological measures as predictors

Previous work has implicated the slope of the audiogram, the dynamic range between thresholds of hearing and thresholds of uncomfortable listening (ULL), and the differences in dynamic range at high and low frequencies as factors which influence benefits from and candidature for amplitude compression (Lunner et al, 1997a; Lunner et al, 1997b; Moore et al, 1992). Thresholds of hearing for pure tones between 250 and 8000 Hz were measured using a standard protocol (British Society of Audiology, 1985), as were thresholds of uncomfortable listening (British Society of Audiology, 1987). In addition to individual values, variables were constructed corresponding to:

1. the dynamic range for each frequency;
2. lower frequency (mean of 500 and 1000 Hz) threshold of hearing, threshold of uncomfortable listening, and dynamic range;
3. higher frequency (mean of 2000 and 4000 Hz) threshold of hearing, threshold of uncomfortable listening, and dynamic range; and
4. difference between higher and lower frequency threshold (audiogram slope), ULL and dynamic range.

Psychoacoustic measures as predictors

Sensorineural hearing loss (SNHL) is accompanied by varying degrees of nonlinear distortion over and above simple loss of audibility. The most obvious manifestation is the reduced dynamic range, particularly at higher frequencies, between thresholds of hearing and thresholds of uncomfortable listening. Abnormalities in frequency resolution, temporal resolution, loudness characteristics, and masking patterns also occur (for an overview see Moore, 1998). Such deficits contribute at least in part to the difficulties that listeners with SNHL experience in understanding speech (particularly at adverse signal-to-noise ratios), and to the limited extent to which hearing aids alleviate their disabilities (Plomp, 1978). Although psychoacoustical characterisation of SNHL is most readily achieved using basic (e.g. pure-tone) stimuli, in general such characterisation relates at best loosely to measures of speech intelligibility after control for hearing thresholds (Humes et al, 1994). In this experiment, we have used speech-based stimuli to investigate how artificial manipulation of some underlying cues impacts on speech intelligibility and relates to the benefits of the different hearing aid fittings.

Each of the manipulations has used a series of 16 vowel-consonant-vowel (VCV) stimuli with five different exemplars produced in quiet by the same talker for each stimulus. Listeners were presented with a single token over headphones, and were presented with the 16 response alternatives on a touch-sensitive computer screen. Each of the 16 VCV stimuli was presented twice, and performance was scored as percent correct for the total of 160 presentations. Two separate manipulations of the stimuli were performed; one to assess susceptibility to spectral and temporal smearing and one to assess susceptibility to upward spread of masking.

SUSCEPTIBILITY TO SPECTRAL AND TEMPORAL SMEARING

Slow-acting AVC hearing aids (one example of which is the *SLOW-SLOW* fitting in the current experiment) aim to maintain the internal short-term dynamics of the input signal, while

adjusting the overall level and spectral shape to match the available dynamic range of a listener with SNHL. In contrast, fast-acting WDRC fittings (one example of which is the *FAST-FAST* fitting) aim to operate on the short-term characteristics of the input signal to improve moment-to-moment audibility. Thus the internal dynamics and inter-relationships among the components of the input signal are subject to potential change. Any hearing aid processing which is successful in its objective of improving moment-to-moment audibility (and some single-channel implementations have not been successful even in that aim –Verschuure et al, 1996), has as an inevitable consequence some reduction in the spectral and temporal contrasts in an input signal with a complex spectral and temporal structure. This is not an issue regarding the integrity of an engineering implementation, but is a necessary consequence of changing the frequency-gain characteristic of a fitting to match the input signal to a reduced residual dynamic range, over time periods that are comparable to the temporal fluctuations in the input signal. It is the spectral and temporal contrasts in a speech signal which carry information. On average, fast-acting WDRC offers little advantage over optimised linear processing when only a single overall input level is used (Moore et al, 1992; Moore et al, 1999) and, on average, appears to confer no consistent incremental advantage over slow-acting AVC (for a more detailed discussion see the companion article – Gatehouse et al, 2006). It has been postulated (Boothroyd et al, 1988; Boothroyd, 1999) that there are some listeners for whom the improvements in moment-to-moment audibility outweigh any consequences of reducing the spectral and temporal contrasts in speech, while for others the converse might be the case. This experiment attempted to address this issue by generating potential predictors using speech tokens which have been subjected to an artificial manipulation to deliberately induce disruptions into the spectral and temporal contrasts.

All processing was performed in the MATLAB™ environment. Each of the 80 (16 × 5) waveform files corresponding to the 80 VCV tokens was processed in turn. Each waveform was divided into eight frequency regions (each 1000 Hz wide) from 0 to 8000 Hz using bandpass filters with nominal skirts of 60 dB per octave (Abed et al, 1984; Trinder, 1982). This then generated eight separate waveform files per VCV token. Each of these eight waveform files was then divided into a series of subfiles of duration 100 ms. The average duration of the VCV tokens was 1300 ms, so this resulted in (on average) 104 (8 × 13) subfiles. Each of these subfiles was then subjected to frequency lowering or raising and/or time advance/delay, either separately or in combination. During any of these manipulations, no attention was paid to artefacts occurring at the frequency or time boundaries. To achieve frequency lowering/raising, for each subfile a random number specified to vary uniformly between -0.1 and +0.1 was generated. This random number for each subfile was used to transpose down or up in frequency by that proportion of the band-centre for that subfile. Thus a random number of +0.05 for a subfile with nominal bandwidth 2000–3000 Hz results in an upward shift of 125 Hz (5% of 2500 Hz) for all elements of that subfile. A second set of random numbers uniformly distributed between -10 and +10 were used to achieve temporal advance/delay for each subfile. Here a value of -5 results in a temporal advance of 5 ms, and +5 a temporal delay of 5 ms. Following these manipulations, each of the 80

VCV tokens was reassembled in processed form. Four conditions were implemented for each of the 80 VCV tokens:

1. separation of each VCV token into the (on average) 104 subfiles, followed by reassembly with no frequency transposition or temporal manipulation (as no attention was paid to artefacts at the frequency and time boundaries, this served as a control condition);
2. frequency raising/lowering alone;
3. temporal advance/delay alone; and
4. frequency raising/lowering and temporal advance/delay operating simultaneously.

The values for the frequency shifting and temporal advance/delay were chosen after informal pilot experiments with normal-hearing listeners which showed that the chosen parameter values did not lead to intelligibility scores which suffered from floor or ceiling effects. It should be emphasised that the manipulations were not designed to mimic the effects of any given hearing aid processing aid fitting (which depend on both the technical implementation and the fitting parameters), but rather as manipulations which could be used to assess the extent to which individual listeners with SNHL were susceptible or resistant to disruption of the spectral and temporal contrasts in a speech signal, largely divorced from audibility considerations.

The three sets of processed 80 VCV tokens were each adjusted to the same RMS level as their control counterpart. The four sets of tokens were each presented twice over headphones, monaurally in the ear to be fitted, at the same comfortable listening level in a randomised order. Results for each condition were expressed as percent correct, and three indices of susceptibility derived:

1. decrease in performance upon frequency shifts;
2. decrease in performance upon temporal shifts;
3. decrease in performance on frequency and temporal shifts combined.

Greater values represent greater susceptibility (lower resistance). Of course, a nominal shift in either frequency or time alone resulted in both frequency and temporal effects in the eventual composite signal.

SUSCEPTIBILITY TO UPWARD SPREAD OF MASKING

Listeners with SNHL suffer widened auditory filters (Moore, 1998) whose bandwidths increase on average with increasing impairment level. Thus listeners with SNHL which slopes from low to high frequencies, the usual configuration, are potentially susceptible to upward spread of masking (USOM). Here, relatively intense low-frequency components of an input signal have the potential to obscure energy at higher frequencies occurring simultaneously with, or close in time to, the low-frequency input (Van Tasell & Trine, 1992). Some aspects of USOM have been implicated in some types of hearing aid fitting, though for relatively constrained test conditions (Van Tasell & Trine, 1992), where in field trials a number of listeners indicated a preference for a fitting with fast-acting WDRC in a low-frequency channel, and slow AVC processing in the high frequencies of a two-channel system. The process whereby compression in the low frequencies reduces more intense low-frequency sounds and hence reduces the opportunity for upward

spread of masking to occur has been invoked as a potential explanation for these findings, though there does not appear to be any direct evidence for this contention (Lunner et al, 1997a; Lunner et al, 1997b). Given this specific hypothesis and the existence of the *FAST-SLOW* fitting in the current experiment, the opportunity was available to address the issue experimentally. As with the psychoacoustic measures of susceptibility to spectral and temporal degradations, an approach using speech, rather than basic pure-tone stimuli has been adopted.

The original VCV stimuli described above were used. As a first step, each of the 80 tokens was low-pass and high-pass filtered at 1600 Hz to produce a pair of subfiles using filters in the MATLAB environment with nominal skirts of 60 dB per octave. The high-pass filtered subfiles were left intact. The temporal envelope of the low-pass subfiles was extracted and that envelope used to modulate white noise stimuli which had themselves been low-pass filtered at 1600 Hz. Thus the low-pass subfiles now have no spectral fine structure, but retain the low-pass temporal envelope of the original VCV tokens.

Measures of susceptibility to upward spread of masking were derived in two stages, by headphone presentation to the ear to be fitted. Firstly, a performance-intensity function was derived for the high-pass VCV subfiles alone. Sets of the 80 subfiles were selected randomly and percent correct score as a function of presentation level ascertained. The results were plotted, and testing continued using increasing presentation levels until asymptotic performance was achieved. The presentation level for the high-pass subfiles was then fixed at a level that yielded 90% of the maximum score for each listener. Testing now proceeded with the introduction of the low-pass subfiles (with no spectral detail, but retaining the original low-frequency temporal envelope). As the level of the low-pass noise is increased, upward spread of masking can occur, and the scores for the intact high-pass VCV tokens can decrease. The results were plotted and fitted with three straight-line segments with:

1. a horizontal portion prior to the onset of upward spread of masking;
2. a linear decrease in VCV score with increase in low-frequency noise level; and
3. a further horizontal portion at chance performance (6.25%).

A nonlinear regression model using SPSS Version 11 software was used to identify the parameters of the various segments, and produces the kneepoint (or onset of upward spread of masking) and the slope of the linear decrease. Inspection of the data showed that the kneepoint was largely a function of audibility and predictable from the audiogram, whereas the slope of the decrease with increasing low-frequency noise level was not. The latter is used as the measure of susceptibility to upward spread of masking. Again, greater values represent greater susceptibility (lower resistance). The retention of the low-frequency envelope in the low-pass noise used to induce USOM was intended to preserve sensitivity to temporally dynamic aspects of USOM, though as will be discussed later, it did have some other potential consequences.

Cognitive capacity as a predictor

The cognitive capacities of normal-hearing and hearing-impaired listeners exert material influence on measured abilities

in speech intelligibility tasks (Wingfield, 1996). In the rather special case of cochlear implantation, where the speech code is represented in a highly nonphysiological manner, listeners' cognitive abilities exert significant leverage on ability to understand speech through the implant (Gantz et al, 1993; Lyxell et al, 1996). In addition, such abilities appear to play a role in speech intelligibility in noise for listeners with moderate SNHL (Lunner, 2003) though data on ability to benefit from amplification has yet to emerge. As part of the relatively rich set of variables in the predictor domain, cognitive capacity was included in the current experiment, so that its role as a predictor of candidature and benefit could be evaluated in relation to other dimensions.

Cognitive abilities were assessed using a visual digit-monitoring task and a visual letter-monitoring task. The former was developed at the University of Iowa (Knutson et al, 1991) and has been used in the cochlear implant experiment referenced above. The letter-monitoring task was developed by colleagues at the MRC Institute of Hearing Research for use in their evaluation of adult cochlear implant services in the United Kingdom. In the digit-monitoring task, single digits between 1 and 8 were presented serially on a computer screen, with an interstimulus interval (ISI) of either 1 or 2 s. The subject's task was to monitor the stream of digits on the screen and to press the keyboard spacebar (prior to arrival of the succeeding digit) when three consecutive digits form an odd-even-odd sequence. The letter-monitoring task was similar in structure, though here the task was to activate the keyboard when three consecutive letters form a recognised word in the English language. More specifically, letters appeared in an alternating sequence of consonants and vowels, and the task was to monitor for real CVC words. The digit and letter monitoring tasks were each performed using the two ISIs, and each condition was presented twice, following a single practice run. The order of the letter-monitoring and digit-monitoring conditions was randomised, though within each, the longer ISI was tested first. For each run, performance was characterised by the value of d' (a statistical measure of the correct and false responses to the target and nontarget sequences), which is relatively immune to overall response biases. Detailed analyses of the interactions between the hearing aid fittings, the speech-test conditions and cognitive capacity are available in Gatehouse et al (2003).

Auditory ecology as a predictor

Although nonlinear amplitude compression in hearing aids would not appear, on average, to offer superior speech intelligibility to linear processing when the linear condition can be optimised, advantages do emerge when a range of presentation levels and signal-to-noise ratios is encountered and listeners are not afforded the opportunity to alter the volume control and/or frequency-gain characteristic (Moore et al, 1992; Moore et al, 1999, Gatehouse et al, 2006). We have suggested elsewhere (Gatehouse et al, 1999) that the range, types and importance of the listening circumstances which individual listeners encounter and are required to function in, is a potentially important aspect of candidature. Preliminary data supported that hypothesis for linear versus amplitude-compression fittings, and encourage recognition of a listener's auditory ecology as one element of candidature. We now extend that hypothesis to embrace non-

linear fittings with differing time constants. Two approaches to the assessment of auditory ecology have been taken:

1. reports from hearing-impaired listeners about their environments and perceptual demands; and
2. acoustical measurements of the environments that listeners encounter.

SELF-REPORT MEASURES

We have reported previously a questionnaire to assess the range and importance of listening demands (Gatehouse et al, 1999), termed the Auditory Lifestyle and Demand Questionnaire (ALDQ). This presents listeners with 24 examples of listening circumstances, and asks them to rate on a three-point scale the frequency with which those circumstances occur in everyday life and on a second three-point scale, the importance of each circumstance to their everyday experience and requirements. The individual questions are available in Gatehouse et al, 1999. The objective of the ALDQ is to characterise the auditory environments that different listeners are required to function in, and to further examine their relative contribution to everyday function via ascertainment of individual importance. The first scale (labelled 'ALD frequency') accesses only the frequency of occurrence data and is scaled so that aggregate responses can span 0–100 arbitrary units. The second scale (labelled 'ALD importance-weighted') multiplies each individual frequency of occurrence by the corresponding importance rating. It is again scaled to span the range 0–100. In both cases, larger values represent a more varied auditory lifestyle.

ACOUSTICAL MEASURES

A second approach to the characterisation of auditory ecology used electronic logging devices developed for the monitoring of workplace noise levels. The instrument (QUEST Q-400 Noise dosimeter) logs each 10-second A-weighted Leq from a lapel microphone to an internal memory. The unit contains sufficient internal memory to store the Leq for each 10-second epoch over an 18-hour time period. The devices were programmed to start logging automatically at 6 am each day, and to switch off at 12 midnight. Listeners were supplied with the devices, and the data were downloaded on a daily basis to a computer for subsequent analysis. Listeners wore the devices for seven alternate days over a 14-day period (to facilitate data download), during the course of which they reported no abnormal life activities (i.e. the period represented a typical two-week period). Listeners completed a diary during the course of each day for which the logging was active. Data were only included for the periods of each day where listeners reported being awake. In principle, the logging could include 45,360 data points, though many listeners reported longer periods of sleep than six hours per day.

In addition to standard descriptive statistics for the data distributions (e.g. mean and standard deviation), two further types of measure to characterise the acoustical patterns were derived. These are aimed at assessing the extent to which there are differences in the acoustical conditions experienced by listeners at different times of day and days of the week, and the extent to which the acoustic environment exhibits variation from sample to sample, for samples close in time. We refer to

these as measures of ‘between-frame variability’ and ‘within-frame variability’, and the measures are derived as follows. For the measures of between-frame variability, the duration of a time-frame was defined. Within that time frame, the mean of all the 10-second Leq values (hereafter referred to as Leq[10]) falling into the time frame was computed. This is referred to as Mean[frame]. The time frame was then advanced by one 10-second sample, and the revised Mean[frame] recomputed. Where a time frame overlapped a day boundary or sleep period, Mean[frame] was not computed. This then generated a set of values of Mean[frame]. A measure of between-frame variability was then defined as the standard deviation of all of the Mean[frame] values, and thus represented the dispersion over the seven-day monitoring period of levels of mean SPL within each time frame. A series of measures of between-frame variability were computed for frame durations of 1, 10, 30, and 60 minutes (corresponding to 6, 60, 180, and 360 samples of Leq[10] respectively). The range of values was chosen in an attempt to allow differentiation between different ecologies, and avoid premature assumptions about eventual predictive leverage.

A series of measures of within-frame variability was derived in an associated manner. Here the duration of a time frame was defined, though on this occasion the standard deviation of all the Leq[10] values falling into that frame was computed. This is referred to as SD[frame]. Again the time frame was advanced by one sample, and the revised SD[frame] re-computed. A set of values for SD[frame] was generated across the seven-day monitoring period, again excluding the day and sleep boundaries. A measure of within-frame variability was then defined as the mean of all of the SD[frame] values, and thus represented the average across the seven-day monitoring period of the dispersions in Leq[10] for each defined duration of time frame. In parallel with the previous procedure, a series of measures of within-frame variability were computed for frame durations of 1, 10, 30, and 60 minutes (corresponding to 6, 60, 180, and 360 samples of Leq[10] respectively).

Data reduction

The companion paper to this article (Gatehouse et al, 2006) used a factor analysis procedure to reduce 16 outcome measures from self-report questionnaires to three factors. A similar approach was taken here to reduce the large number of potential predictor indices, given the availability of the audiological, psychoacoustical, cognitive, and ecological parameters. This was further required given the novel nature of many of the potential predictors and the accompanying uncertainty over the relevance of individual parameter values. All factor analyses operated on the covariance matrix, extracted principal components with Eigenvalues greater than unity, and performed oblique rotation

Table 1. Summary of the variables which load predominantly on the two emergent factors from the audiological parameters

<i>Hearing Loss factor</i>	<i>Slope and Dynamic Range factor</i>
Threshold at 1000 Hz	Audiogram slope
Threshold at 2000 Hz	High frequency dynamic range
Threshold at 4000 Hz	Difference in dynamic range at high versus low frequency
–	Threshold at 8000 Hz

which allowed, but did not require, that multiple factors to be correlated and not orthogonal. All factor analyses were stable in both form and content against random deletion of 10% of the original data sets.

AUDIOLOGICAL MEASURES

Hearing thresholds, thresholds of uncomfortable listening, and the dynamic ranges and derived summary indices for slope and difference in dynamic range were input variables to a factor analysis as described above. Two factors were isolated, with the variables shown in Table 1 having factor loading >0.7. In view of these groupings, the factors were labelled as *Hearing Loss* factor, and *Slope and Dynamic Range* factor. Factor scores for each were derived using the SPSS regression option, resulting in standardised z-scores for each. Note that in the derivation of the factor scores, all the input variables and their associated factors loadings were used, and not just those listed in Table 1 (the latter would correspond to a sub-scale rather than a factor score approach, as discussed in Gatehouse et al, 2006). The *Hearing Loss* factor increased with increasing hearing thresholds, and the *Slope and Dynamic Range* factor increased as each of the audiogram slope, high-frequency dynamic range, difference in dynamic range at high versus low frequencies, and the 8000 Hz hearing threshold increased.

PSYCHOACOUSTIC MEASURES

The three measures of susceptibility to spectral and temporal degradation, the measure of susceptibility to upward spread of masking, and the hearing thresholds between 250 and 8000 Hz were input variables in a separate factor analysis. Two factors were isolated, with the variables shown in Table 2 having factor loadings >0.7. In view of the patterns these were labelled as *Susceptibility to Spectral and Temporal Smearing* factor, and *Susceptibility to Upward Spread of Masking* factor. It is instructive to note that, even though the measures were designed to be largely independent of audibility considerations, each of the two resultant factors was still influenced by some aspect of the audiogram. It should also be noted that the measure of spectral degradation alone did not load heavily on the first factor. As before, factor scores were derived via a regression approach.

COGNITIVE FUNCTION

The eight variables assessing cognitive capacity (letter/digit monitoring, 1- versus 2-second ISI, replicates 1 and 2) entered a factor analysis. A single *cognitive function* factor emerged, and

Table 2. Summary of the variables which load predominantly on the two emergent factors from the psychoacoustical parameters

<i>Susceptibility to Spectral and Temporal Smearing Factor</i>	<i>Susceptibility to Upward Spread of Masking Factor</i>
Susceptibility to combined spectral and temporal smearing	Susceptibility to upward spread of masking
Susceptibility to temporal smearing alone	Threshold at 250 Hz
Threshold at 8000 Hz	–

Table 3. Summary of the variables which load predominantly on the three emergent factors from the noise dosimeter parameters

<i>Overall dosimeter distribution factor</i>	<i>Dosimeter within-frame variability factor</i>	<i>Dosimeter between-frame variability factor</i>
Mean level in dB A	Within-frame variability using 1 minute frame length	Between-frame variability using 10 minute frame length
Overall standard deviation	Within-frame variability using 10 minute frame length	Between-frame variability using 30 minute frame length
Interquartile range	–	–

the factor score was computed via the regression option in the SPSS factor analysis.

AUDITORY ECOLOGY

It was unclear at the outset, how the self-report measures from the Auditory Lifestyle and Demand Questionnaire (ALDQ) might relate to the acoustical indices, and the variables were fed into separate analyses. A single factor emerged from the two-scale combinations in the ALDQ. In contrast, three factors were isolated from the range of acoustical indices. The variables loading at >0.7 are shown in Table 3. The first factor (*overall dosimeter distribution*) was associated with parameters of the overall distribution of the monitoring data, while the second and third factors (*within-frame variability* and *between-frame variability*) related specifically to the derived indices for within- and between-frame variability, with the latter having more emphasis on longer frame lengths. As before, the three factor scores were computed via a regression approach.

DERIVED PREDICTORS

The sets of factor analyses have isolated nine predictor factors. These are listed in Table 4. Two factors were isolated from the audiometric data, two factors were associated with psychoacoustics in SNHL, four factors (one self-report and three acoustic) were associated with auditory ecology, and a single factor assessed cognitive capacity. Larger values for the *hearing loss* predictor factor were associated with greater impairment; larger values of the *slope and dynamic range* factor with more sloping losses and more restricted dynamic ranges; larger values of the *spectral and temporal smearing* factor and the *upward spread of masking* factor with greater susceptibilities, larger values of the *overall dosimeter distribution* factor with louder environments; greater values for *between-frame variability* and *within-frame variability* factors with greater variability; and

Table 4. Summary labels for the nine factors in the predictor domain

<i>Labels for the predictor factors</i>
Hearing loss
Slope and dynamic range
Susceptibility to spectral and temporal smearing
Susceptibility to upward spread of masking
Overall dosimeter distribution
Dosimeter within-frame variability
Dosimeter between-frame variability
ALD questionnaire
Cognitive Function

larger values of the *cognitive function* factor with greater cognitive capacity.

The nine potential predictor factors were used to investigate their influence on each of the four benefit factors derived in the companion article (Gatehouse et al, 2006), using a correlational approach. To interpret the subsequent correlations it is necessary to have some prior knowledge of the interrelationships amongst the nine predictor factors, and Table 5 shows their correlation matrix. As discussed in the companion article there were two primary stratification variables based upon difference in dynamic range between low and high frequencies and the number of volunteered listening circumstances in the Glasgow Hearing Aid Benefit Profile (Gatehouse, 1999). Inspection of Table 5 shows that the stratification has been successful in that there are no significant correlations between the slope and dynamic range factor and any of the factors concerned with auditory ecology. There are a number of significant relationships which are discussed here in turn. There is a significant negative correlation between the *hearing loss* factor and the *auditory lifestyle and demand* factor such that individuals with greater degrees of impairment report more restricted auditory lifestyles. Such a correlation is consistent with the suggestion that impaired hearing can be implicated in social isolation and withdrawal. There are some significant and plausible interrelationships between the dosimeter measures and also an unexplained correlation between the *overall dosimeter distribution* and *cognitive function*. Overall, correlations between the predictor factors are the exception rather than the rule, and therefore the predictor factors that do correlate with benefit are unlikely to be simple surrogates of each other.

Results

Correlates of benefit for each individual hearing aid fitting

Table 6, 7, 8, 9, and 10 show the correlations between the nine predictor factors and the four benefit factors for the *NAL-RP* fitting, the *LINEAR* fitting, the *SLOW-SLOW* fitting, the *FAST-FAST* fitting and the *FAST-SLOW* fitting respectively. Each table contains the Pearson Correlation coefficient, the Spearman Rank Correlation coefficient, and the correlation between the relevant predictor factor and benefit factor having partialled out the *hearing loss* predictor factor and the *slope and dynamic range* predictor factor, as well as the significance level associated with each coefficient. The comparison of the Pearson and Spearman Correlation coefficients allows appreciation of the influence of outliers in the data, and the comparison of each with the partial correlation allows an appreciation of the extent to which the measures available from the audiogram might preempt the influence of any subsequent predictor factor. The latter

Table 5. Correlations amongst the nine predictor factors (* = $p < .05$; ** = $p < .01$)

	Slope and dynamic range	Susceptibility to upward spread of masking	Susceptibility to spectral and temporal smearing	Cognitive function	ALD questionnaire	Overall dosimeter distribution	Dosimeter within-frame variability	Dosimeter between-frame variability
Hearing loss	-.21	.10	.03	.22	-.28* ($p < .05$)	.15	0.2	-.25
Slope and dynamic range		-.12	.01	-.08	.12	.21	.01	.03
Susceptibility to upward spread of masking			-.22	.03	-.04	.06	.06	.12
Susceptibility to spectral and temporal smearing				-.09	.27	.12	-.06	.17
Cognitive function					-.08	.30* ($p < .05$)	.17	.04
ALD questionnaire						.01	.34* ($p < .05$)	.41** ($p < .01$)
Overall dosimeter distribution							.17	.37** ($p < .01$)
Dosimeter within-frame variability								.32* ($p < .05$)
Dosimeter between-frame variability								

is of interest given the universal availability of an audiogram prior to hearing aid fitting and a desire to identify factors that deliver predictive leverage beyond the audiogram. In reporting the results we concentrate on those findings which are broadly consistent across the three types of correlation in an attempt to avoid capitalising on idiosyncratic results.

Table 6 shows the pattern of correlations for the *NAL-RP* fitting. There is a significant negative correlation between the *slope and dynamic range* factor and the *listening comfort* benefit factor, such that those listeners with more sloping audiograms, more restricted dynamic ranges, and greater differences between dynamic range at high and low frequencies report lower *listening comfort*. Although the correlations between *slope and dynamic range* and the *satisfaction* and *reported intelligibility* benefit factors are in the same direction they do not achieve statistical significance. There are also significant negative correlations between the *auditory lifestyle and demand* predictor factor and all three of the benefit factors in the self-report domain, in the direction that individuals with more restricted reports of auditory lifestyles exhibit greater benefit from the *NAL-RP* fitting. This finding for reports of auditory lifestyles is replicated for both the *dosimeter between-frame variability* and the *dosimeter within-frame variability* predictor factors in the same direction, though with stronger findings for the *between-frame* factor compared to the *within-frame* factor.

Table 7 shows the results for the *LINEAR* fitting. Comparison of Tables 6 and 7 demonstrates broadly similar results. The differences in frequency response between the *NAL-RP* fitting and the *LINEAR* fitting, and the availability of a volume control in *NAL-RP* and its absence in *LINEAR*, apparently are not substantial influences, and any subsequent differences in pattern which might emerge between the two linear and the three nonlinear fittings should not be attributed to those influences. There are though, some minor differences in the patterns for the *NAL-RP* and the *LINEAR* fittings, particularly in terms of the *slope and dynamic range* factor that could plausibly be attributed to the use of a volume control. For instance, the correlations between the two audiometric predictors and the *speech test* benefit factor are substantial for the *LINEAR* fitting, but nonsignificant for the *NAL-RP* fitting. Note that for the *NAL-RP* fitting, the volume control was adjusted at the start of the speech testing procedure but held constant thereafter (for full details see the companion article in this volume – Gatehouse et al, 2006).

Table 8 shows the correlations for the *SLOW-SLOW* fitting. In contrast to the two linear fittings, there is now a positive correlation between the *slope and dynamic range* predictor factor and the three benefit factors in the self-report domain, so that listeners with greater audiogram slopes, reductions in dynamic range and greater differences between dynamic range at high as opposed to low frequencies report greater benefit from this nonlinear fitting. There are also positive correlations between the *auditory lifestyle and demand* predictor factors and the three benefit factors such that listeners with greater reported range of auditory environments report greater benefit, again contrasting with the two linear fittings. There are also significant correlations between the *dosimeter between-frame variability* predictor factor and the self-report benefit factors. These are greater and more pervasive than the correlations with the *dosimeter within-frame variability* predictor factor.

Table 6. Correlations between the four benefit factors and the nine predictor factors for the *NAL-RP* fitting. The table includes the Pearson correlation (parametric), the Spearman correlation (nonparametric), and the Partial Correlation (after control for the *hearing loss* factor and the *slope and dynamic range* factor)

	<i>Listening Comfort benefit factor</i>	<i>Satisfaction benefit factor</i>	<i>Reported Intelligibility benefit factor</i>	<i>Speech Test benefit factor</i>
<i>Hearing loss</i> predictor factor				
Pearson Correlation	.08	.08	-.02	.15
Spearman Correlation	.12	.10	-.00	.17
Partial Correlation	-	-	-	-
<i>Slope and dynamic range</i> predictor factor				
Pearson Correlation	-.40**	-.25	-.21	-.00
Spearman Correlation	-.46**	-.25	-.26	-.08
Partial Correlation	-	-	-	-
<i>Upward spread of masking</i> predictor factor				
Pearson Correlation	-.02	-.07	-.13	-.04
Spearman Correlation	-.02	.03	-.11	-.00
Partial Correlation	-.11	-.12	-.17	-.05
<i>Effect of spectral and temporal smearing</i> predictor factor				
Pearson Correlation	-.04	-.13	-.03	-.18
Spearman Correlation	-.05	-.17	-.03	-.17
Partial Correlation	-.03	-.12	-.02	-.19
<i>Cognitive function</i> predictor factor				
Pearson Correlation	.03	.04	-.16	-.10
Spearman Correlation	.09	.09	-.08	-.10
Partial Correlation	-.01	.01	-.17	-.13
<i>Auditory lifestyle and demand</i> predictor factor				
Pearson Correlation	-.53**	-.52**	-.48**	-.11
Spearman Correlation	-.51**	-.51**	-.48**	-.08
Partial Correlation	-.57**	-.53**	-.51**	-.07
<i>Overall dosimeter distribution</i> predictor factor				
Pearson Correlation	-.09	-.15	-.22	.03
Spearman Correlation	-.14	-.11	-.23	.04
Partial Correlation	-.07	-.15	-.19	-.02
<i>Dosimeter between-frame variability</i> predictor factor				
Pearson Correlation	-.34*	-.32*	-.40**	.05
Spearman Correlation	-.37**	-.36**	-.41**	.16
Partial Correlation	-.38**	-.34*	-.41**	.04
<i>Dosimeter within-frame variability</i> predictor factor				
Pearson Correlation	-.20	-.18	-.35*	-.30*
Spearman Correlation	-.29*	-.24	-.39**	-.28*
Partial Correlation	-.22	-.18	-.37**	-.28

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

Table 9 shows the correlations for the *FAST-FAST* fitting. In common with the results from the *SLOW-SLOW* fitting there are again positive correlations between both the *slope and dynamic range* predictor factor and the *auditory lifestyle and demand* predictor factor and the three self-report benefit factors. The measures of acoustic ecology now show significant correlations between the three self-reported benefit factors and the *within-frame variability* as opposed to the *between-frame variability* predictor factor. Thus if one interprets the *between-frame variability* factor as some form of index of the extent to

which different sections of the auditory experience differ from each other, and the *within-frame variability* as some index of the variability within a section of the auditory experience, then this is consistent with the putative aims of fast-acting wide dynamic range compression as opposed to slow-acting automatic volume control. Table 9 also shows significant negative correlations between *susceptibility to spectral and temporal smearing* predictor factor and the *speech test* benefit factor, such that individuals who are more susceptible to the consequences of artificially disrupting spectral and temporal cues in the speech

Table 7. Correlations between the four benefit factors and the nine predictor factors for the *LINEAR* fitting. The table includes the Pearson correlation (parametric), the Spearman correlation (nonparametric), and the Partial Correlation (after control for the *hearing loss* factor and the *slope and dynamic range* factor)

	<i>Listening Comfort benefit factor</i>	<i>Satisfaction benefit factor</i>	<i>Reported Intelligibility benefit factor</i>	<i>Speech Test benefit factor</i>
<i>Hearing loss</i> predictor factor				
Pearson Correlation	-.04	.09	-.03	.29*
Spearman Correlation	-.03	.11	-.03	.42**
Partial Correlation	-	-	-	-
<i>Slope and dynamic range</i> predictor factor				
Pearson Correlation	-.20	-.29*	-.29*	-.50*
Spearman Correlation	-.23	-.30*	-.31*	-.56**
Partial Correlation	-	-	-	-
<i>Upward spread of masking</i> predictor factor				
Pearson Correlation	-.16	.00	-.14	-.10
Spearman Correlation	-.06	.17	-.03	-.06
Partial Correlation	-.20	.06	-.21	-.25
<i>Effect of spectral and temporal smearing</i> predictor factor				
Pearson Correlation	-.05	-.16	-.05	-.06
Spearman Correlation	-.05	-.16	-.04	.05
Partial Correlation	-.03	-.16	-.03	-.07
<i>Cognitive function</i> predictor factor				
Pearson Correlation	-.09	-.10	-.04	.06
Spearman Correlation	-.03	-.08	.02	.10
Partial Correlation	-.10	-.14	-.05	-.02
<i>Auditory lifestyle and demand</i> predictor factor				
Pearson Correlation	-.39**	-.41**	-.46**	-.09
Spearman Correlation	-.43**	-.45**	-.50**	-.15
Partial Correlation	-.42**	-.42**	-.51**	-.00
<i>Overall dosimeter distribution</i> predictor factor				
Pearson Correlation	-.14	-.23	-.22	-.05
Spearman Correlation	-.13	-.18	-.20	-.07
Partial Correlation	-.11	-.24	-.19	-.09
<i>Dosimeter between-frame variability</i> predictor factor				
Pearson Correlation	-.40*	-.30*	-.36*	-.07
Spearman Correlation	-.34*	-.34*	-.36*	-.04
Partial Correlation	-.35*	-.32*	-.38*	-.11
<i>Dosimeter within-frame variability</i> predictor factor				
Pearson Correlation	-.26	-.25	-.34*	-.23
Spearman Correlation	-.29*	-.28	-.37**	-.33*
Partial Correlation	-.29	-.26	-.38*	-.24

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

signal gain less benefit from the *FAST-FAST* fitting on laboratory speech tests. There is also a positive correlation between the *cognitive function* predictor factor and reported and measured speech performance, such that individuals with greater cognitive capacities exhibit greater reported and measured benefit from the *FAST-FAST* fitting.

Table 10 shows the pattern of correlations for the *FAST-SLOW* fitting. In common with the other two nonlinear fittings, there are positive correlations of benefit with the *slope and dynamic range* predictor factor and also with the *auditory*

lifestyle and demand predictor factor. Their interpretation is similar. In common with the *FAST-FAST* fitting, the *FAST-SLOW* fitting which contains some element of fast-acting wide dynamic range compression also has significant correlations with the *within-frame variability predictor* factor. These are stronger and more pervasive than correlations with the *between-frame variability* factor. Unlike the *FAST-FAST* fitting, for the *FAST-SLOW* fitting there is no correlation between the *susceptibility to spectral and temporal smearing* predictor factor and either *reported intelligibility* or *speech test* benefit, but these

Table 8. Correlations between the four benefit factors and the nine predictor factors for the *SLOW-SLOW* fitting. The table includes the Pearson correlation (parametric), the Spearman correlation (nonparametric), and the Partial correlation (after control for the *hearing loss* factor and the *slope and dynamic range* factor)

	<i>Listening Comfort benefit factor</i>	<i>Satisfaction benefit factor</i>	<i>Reported Intelligibility benefit factor</i>	<i>Speech Test benefit factor</i>
<i>Hearing loss</i> predictor factor				
Pearson Correlation	-.16	-.28	-.23	.13
Spearman Correlation	-.15	-.26	-.21	.11
Partial Correlation	-	-	-	-
<i>Slope and dynamic range</i> predictor factor				
Pearson Correlation	.54**	.56**	.45**	.09
Spearman Correlation	.55**	.58**	.51**	.10
Partial Correlation	-	-	-	-
<i>Upward spread of masking</i> predictor factor				
Pearson Correlation	-.12	-.09	-.13	-.13
Spearman Correlation	-.09	-.06	-.13	-.03
Partial Correlation	-.02	.03	-.05	-.12
<i>Effect of spectral and temporal smearing</i> predictor factor				
Pearson Correlation	.05	-.05	.04	-.19
Spearman Correlation	.02	-.07	.02	-.24
Partial Correlation	.04	-.07	.04	-.20
<i>Cognitive function</i> predictor factor				
Pearson Correlation	-.30*	-.29*	-.30*	-.05
Spearman Correlation	-.26	-.22	-.27	-.14
Partial Correlation	-.30	-.27	-.27	-.07
<i>Auditory lifestyle and demand</i> predictor factor				
Pearson Correlation	.38**	.48**	.38*	.02
Spearman Correlation	.38**	.51**	.41**	-.02
Partial Correlation	.41**	.51**	.37*	.06
<i>Overall dosimeter distribution</i> predictor factor				
Pearson Correlation	-.04	.01	.05	.09
Spearman Correlation	.03	.14	.07	.03
Partial Correlation	-.09	.02	.07	.04
<i>Dosimeter between-frame variability</i> predictor factor				
Pearson Correlation	.34*	.35*	.33*	.09
Spearman Correlation	.34*	.37**	.33*	.07
Partial Correlation	.43**	.46**	.40**	.09
<i>Dosimeter within-frame variability</i> predictor factor				
Pearson Correlation	.19	.22	.22	-.12
Spearman Correlation	.20	.29*	.19	-.18
Partial Correlation	.22	.25	.23	-.10

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

are correlated with the *upward spread of masking* predictor factor. A simple interpretation would be to support the hypothesis whereby fast-acting compression of the low-frequency channel, combined with preservation of the fine structure in the high-frequency channel in the *FAST-SLOW* fitting, might reduce upward spread of masking compared to fast-acting wide dynamic range compression in both channels (the *FAST-FAST* fitting). Therefore the former might be more beneficial to those

individuals with higher susceptibility to upward spread of masking. We do though raise a caution concerning this simple interpretation in the discussion section.

Patterns of correlations in Table 6, 7, 8, 9, and 10 demonstrate clearly that considerations of psychoacoustic capacities over and above simple audiometric hearing levels and audiometric profiles, consideration of cognitive function and both self-reports and measures of auditory ecology do exert significant

Table 9. Correlations between the four benefit factors and the nine predictor factors for the *FAST-FAST* fitting. The table includes the Pearson correlation (parametric), the Spearman correlation (nonparametric), and the Partial Correlation (after control for the *hearing loss* factor and the *slope and dynamic range* factor)

	<i>Listening Comfort benefit factor</i>	<i>Satisfaction benefit factor</i>	<i>Reported Intelligibility benefit factor</i>	<i>Speech Test benefit factor</i>
<i>Hearing loss</i> predictor factor				
Pearson Correlation	-.27	-.18	-.24	.10
Spearman Correlation	-.20	-.26	-.20	-.01
Partial Correlation	-	-	-	-
<i>Slope and dynamic range</i> predictor factor				
Pearson Correlation	.48**	.35*	.32*	.18
Spearman Correlation	.51**	.41**	.36**	.22
Partial Correlation	-	-	-	-
<i>Upward spread of masking</i> predictor factor				
Pearson Correlation	-.11	-.02	-.05	-.09
Spearman Correlation	-.23	-.00	-.01	-.04
Partial Correlation	-.01	.06	.02	-.06
<i>Effect of spectral and temporal smearing</i> predictor factor				
Pearson Correlation	.08	.15	-.25	-.37**
Spearman Correlation	.07	.15	-.36*	-.44**
Partial Correlation	.09	.16	-.27	-.40*
<i>Cognitive function</i> predictor factor				
Pearson Correlation	.01	.11	.30*	.27*
Spearman Correlation	-.07	.01	.23	.33*
Partial Correlation	.09	.17	.39**	.28
<i>Auditory lifestyle and demand</i> predictor factor				
Pearson Correlation	.42**	.45**	.37**	-.16
Spearman Correlation	.41**	.51**	.34*	-.14
Partial Correlation	.42**	.45**	.34*	-.14
<i>Overall dosimeter distribution</i> predictor factor				
Pearson Correlation	.23	.20	.24	.16
Spearman Correlation	.24	.23	.28*	.18
Partial Correlation	.30	.23	.30	.11
<i>Dosimeter between-frame variability</i> predictor factor				
Pearson Correlation	.23	.21	.24	.14
Spearman Correlation	.16	.11	.30*	.09
Partial Correlation	.29	.24	.28	.15
<i>Dosimeter within-frame variability</i> predictor factor				
Pearson Correlation	.43**	.43**	.32*	-.05
Spearman Correlation	.43**	.43**	.35*	.05
Partial Correlation	.47**	.45**	.32*	-.02

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

leverage in terms of benefit in the self-report and speech test domains, and that these patterns of correlation differ across the fittings in ways that are broadly interpretable.

Age is a variable that can influence hearing aid benefit, though arguably in different directions dependent on the domain of outcome. In the current sample, age was not a significant correlate for any of the four benefit domains in any of the five fittings. In addition age was not a significant correlate of cognitive capacity, unlike the general finding in population samples.

Correlations with differential benefit between fittings

It is of interest to gain insight not only into the correlates of benefit of a particular fitting, but also correlates of the extent to which one fitting offers either more or less benefit than a potential alternative. There are 10 possible comparisons within the five fittings and we here select three for more detailed inspection, as these three provide the maximum contrasts. Note that the sign of any given correlation should be interpreted in the light of the direction of each individual factor.

Table 10. Correlations between the four benefit factors and the nine predictor factors for the *FAST-SLOW* fitting. The table includes the Pearson correlation (parametric), the Spearman correlation (nonparametric), and the Partial Correlation (after control for the *hearing loss* factor and the *slope and dynamic range* factor)

	<i>Listening Comfort benefit factor</i>	<i>Satisfaction benefit factor</i>	<i>Reported Intelligibility benefit factor</i>	<i>Speech Test benefit factor</i>
<i>Hearing loss</i> predictor factor				
Pearson Correlation	-.23	-.21	-.23	-.01
Spearman Correlation	-.18	-.23	-.21	-.04
Partial Correlation	-	-	-	-
<i>Slope and dynamic range</i> predictor factor				
Pearson Correlation	.55**	.55**	.51**	.45**
Spearman Correlation	.61**	.59**	.57**	.46**
Partial Correlation	-	-	-	-
<i>Upward spread of masking</i> predictor factor				
Pearson Correlation	-.20	.07	.21	.25
Spearman Correlation	-.14	.14	.27	.37*
Partial Correlation	-.11	.23	.38*	.37*
<i>Effect of spectral and temporal smearing</i> predictor factor				
Pearson Correlation	.10	.05	.02	-.10
Spearman Correlation	.04	-.01	-.04	-.20
Partial Correlation	.11	.04	.01	-.14
<i>Cognitive function</i> predictor factor				
Pearson Correlation	-.12	-.16	-.02	.06
Spearman Correlation	-.12	-.12	.04	.12
Partial Correlation	-.06	-.12	.05	.10
<i>Auditory lifestyle and demand</i> predictor factor				
Pearson Correlation	.43**	.41**	.39**	.09
Spearman Correlation	.37**	.42**	.38**	.11
Partial Correlation	.45**	.44**	.39**	.09
<i>Overall dosimeter distribution</i> predictor factor				
Pearson Correlation	.06	.09	.18	.28*
Spearman Correlation	.13	.15	.24	.33*
Partial Correlation	.06	.10	.22	.26
<i>Dosimeter between-frame variability</i> predictor factor				
Pearson Correlation	.25	.21	.25	.11
Spearman Correlation	.22	.16	.21	.10
Partial Correlation	.33	.28	.32	.14
<i>Dosimeter within-frame variability</i> predictor factor				
Pearson Correlation	.32*	.32*	.32*	.00
Spearman Correlation	.33*	.39**	.35*	.04
Partial Correlation	.37*	.37*	.36*	.02

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

Table 11 correlates the nine predictor factors with the extent to which the *FAST-FAST* fitting delivers greater benefit scores than the *LINEAR* fitting. Given that for the *LINEAR* fitting there is a negative correlation between benefit and the *slope and dynamic range* predictor factor, while for the *FAST-FAST* fitting that correlation is positive, it is not surprising that there is now a strong correlation between the advantage of *FAST-FAST* over

LINEAR and the *slope and dynamic range* predictor factor. A similar consideration drives the positive correlations between the three self-report benefit measures and the *auditory lifestyle and demand* predictor factor, and also the dosimeter variability factors, with stronger and more pervasive correlations for the *within-frame variability* predictor than the *between-frame variability* predictor. The *susceptibility to spectral and temporal*

Table 11. Correlations between the four benefit factors and the nine predictor factors for the advantage of the *FAST-FAST* fitting over the *LINEAR* fitting. The table includes the Pearson correlation (parametric), the Spearman correlation (nonparametric), and the Partial correlation (after control for (a), the *hearing loss* factor and (b), the *slope and dynamic range* factor)

	<i>Listening Comfort benefit factor</i>	<i>Satisfaction benefit factor</i>	<i>Reported Intelligibility benefit factor</i>	<i>Speech Test benefit factor</i>
<i>Hearing loss</i> predictor factor				
Pearson Correlation	-.16	-.18	-.17	-.06
Spearman Correlation	-.15	-.19	-.16	-.13
Partial Correlation	-	-	-	-
<i>Slope and dynamic range</i> predictor factor				
Pearson Correlation	.43**	.41**	.36**	.40**
Spearman Correlation	.48**	.45**	.37**	.45**
Partial Correlation	-	-	-	-
<i>Upward spread of masking</i> predictor factor				
Pearson Correlation	.01	-.01	.02	-.02
Spearman Correlation	-.12	-.12	.02	.05
Partial Correlation	.11	.08	.10	.06
<i>Effect of spectral and temporal smearing</i> predictor factor				
Pearson Correlation	.08	.19	-.17	-.28*
Spearman Correlation	.16	.26	-.22	-.33*
Partial Correlation	.08	.20	-.19	-.32*
<i>Cognitive function</i> predictor factor				
Pearson Correlation	.06	.13	.24	.20
Spearman Correlation	.00	.09	.19	.24
Partial Correlation	.11	.20	.32*	.25
<i>Auditory lifestyle and demand</i> predictor factor				
Pearson Correlation	.49**	.55**	.46**	-.09
Spearman Correlation	.51**	.57**	.46**	-.05
Partial Correlation	.51**	.57**	.47**	-.12
<i>Overall dosimeter distribution</i> predictor factor				
Pearson Correlation	.23	.27	.27	.16
Spearman Correlation	.23	.33*	.37**	.18
Partial Correlation	.25	.30	.31	.14
<i>Dosimeter between-frame variability</i> predictor factor				
Pearson Correlation	.33*	.31*	.32*	.15
Spearman Correlation	.30*	.28*	.40**	.09
Partial Correlation	.38*	.36*	.36*	.18
<i>Dosimeter within-frame variability</i> predictor factor				
Pearson Correlation	.42**	.45**	.38**	.08
Spearman Correlation	.41**	.43**	.45**	.17
Partial Correlation	.47**	.49**	.40*	.09

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

smearing factor also has a negative correlation with the advantage of *FAST-FAST* over *LINEAR*, and retains the earlier interpretation.

Table 12 correlates the nine predictor factors with the advantage of the *SLOW-SLOW* fitting over the *LINEAR* fitting. In common with other nonlinear fittings, the *SLOW-SLOW* fitting offers advantages over *LINEAR* for listeners with greater values of the slope and dynamic range factor and greater reported auditory lifestyle and demand. Consistent with the individual data for the *SLOW-SLOW* and *LINEAR* fittings, the

correlation with the *between-frame variability* factor is stronger and more pervasive than the *within-frame variability* factor. Both of these patterns of results are highly consistent with and directly derived from data for the individual fittings.

Given that the previous results have provided statistical leverage in terms of predictors to differentiate linear from nonlinear fittings, it is of interest to investigate whether any of the nine predictor factors exert any leverage in differentiating the two extremes of nonlinear fittings (i.e. the *FAST-FAST* and *SLOW-SLOW* fittings). Table 13 correlates the nine predictors

Table 12. Correlations between the four benefit factors and the nine predictor factors for the advantage of the *SLOW-SLOW* fitting over the *LINEAR* fitting. The table includes the Pearson correlation (parametric), the Spearman correlation (nonparametric), and the Partial correlation (after control for the *hearing loss* factor and the *slope and dynamic range* factor)

	<i>Listening Comfort benefit factor</i>	<i>Satisfaction benefit factor</i>	<i>Reported Intelligibility benefit factor</i>	<i>Speech Test benefit factor</i>
<i>Hearing loss</i> predictor factor				
Pearson Correlation	.08	-.25	-.13	-.17
Spearman Correlation	-.08	-.29*	-.13	-.22
Partial Correlation	-	-	-	-
<i>Slope and dynamic range</i> predictor factor				
Pearson Correlation	.50**	.56**	.46**	.58**
Spearman Correlation	.55**	.61**	.52**	.70**
Partial Correlation	-	-	-	-
<i>Upward spread of masking</i> predictor factor				
Pearson Correlation	.04	-.06	.01	-.02
Spearman Correlation	.01	-.13	-.04	.11
Partial Correlation	.15	.06	.11	.12
<i>Effect of spectral and temporal smearing</i> predictor factor				
Pearson Correlation	.06	.07	.05	-.12
Spearman Correlation	.04	.04	.05	-.20
Partial Correlation	.05	.07	.05	-.16
<i>Cognitive function</i> predictor factor				
Pearson Correlation	-.13	-.13	-.16	-.11
Spearman Correlation	-.15	-.14	-.21	-.12
Partial Correlation	-.11	-.08	-.13	-.07
<i>Auditory lifestyle and demand</i> predictor factor				
Pearson Correlation	.53**	.59**	.53**	.11
Spearman Correlation	.54**	.64**	.59**	.13
Partial Correlation	.61**	.66**	.57**	.07
<i>Overall dosimeter distribution</i> predictor factor				
Pearson Correlation	.08	.16	.18	.14
Spearman Correlation	.12	.21	.20	.16
Partial Correlation	.03	.19	.18	.14
<i>Dosimeter between-frame variability</i> predictor factor				
Pearson Correlation	.47**	.43**	.43**	.16
Spearman Correlation	.44**	.43**	.37**	.17
Partial Correlation	.56**	.56**	.50**	.22
<i>Dosimeter within-frame variability</i> predictor factor				
Pearson Correlation	.31*	.31*	.35*	.12
Spearman Correlation	.33*	.34*	.35*	.10
Partial Correlation	.38*	.36*	.40*	.14

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

with the additional advantage of the *FAST-FAST* fitting over the *SLOW-SLOW* fitting. The thresholds of hearing and thresholds of uncomfortable listening which underpin the *hearing loss* and *slope and dynamic range* predictor factors exert no leverage here, as the *slope and dynamic range* correlations with benefit in the individual fittings are in the same direction and of similar magnitude. However, because the direction of the correlations with *cognitive function* were in contrary directions

(positive for *FAST-FAST* and negative for *SLOW-SLOW*), the *cognitive function* predictor factor now has significant leverage. This is in the direction that those listeners with greater degrees of cognitive capacity are likely to gain more rather than less benefit from *FAST-FAST* as opposed to *SLOW-SLOW*, while conversely those listeners with less cognitive capacity will favour the alternative contrast. The effects of *susceptibility to spectral and temporal smearing* are as one would expect based on the

Table 13. Correlations between the four benefit factors and the nine predictor factors for the advantage of the *FAST-FAST* fitting over the *SLOW-SLOW* fitting. The table includes the Pearson correlation (parametric), the Spearman correlation (nonparametric), and the Partial correlation (after control for the *hearing loss* factor and the *slope and dynamic range* factor)

	<i>Listening Comfort benefit factor</i>	<i>Satisfaction benefit factor</i>	<i>Reported Intelligibility benefit factor</i>	<i>Speech Test benefit factor</i>
<i>Hearing loss</i> predictor factor				
Pearson Correlation	-.17	.03	-.14	.03
Spearman Correlation	-.17	.02	-.08	-.01
Partial Correlation	-	-	-	-
<i>Slope and dynamic range</i> predictor factor				
Pearson Correlation	.11	-.07	.11	.12
Spearman Correlation	.08	-.09	.01	.14
Partial Correlation	-	-	-	-
<i>Upward spread of masking</i> predictor factor				
Pearson Correlation	-.03	.06	.02	-.01
Spearman Correlation	-.08	.05	.09	-.02
Partial Correlation	.00	.05	.05	.01
<i>Effect of spectral and temporal smearing</i> predictor factor				
Pearson Correlation	.05	.22	-.31*	-.26
Spearman Correlation	.14	.27	-.36**	-.29*
Partial Correlation	.06	.23	-.31*	-.27
<i>Cognitive function</i> predictor factor				
Pearson Correlation	.26	.39**	.51**	.30*
Spearman Correlation	.24	.43**	.55**	.39**
Partial Correlation	.30*	.39**	.56**	.31*
<i>Auditory lifestyle and demand</i> predictor factor				
Pearson Correlation	.17	.13	.21	-.17
Spearman Correlation	.20	.14	.17	-.18
Partial Correlation	.13	.14	.18	-.17
<i>Overall dosimeter distribution</i> predictor factor				
Pearson Correlation	.30*	.23	.24	.11
Spearman Correlation	.27	.21	.27	.16
Partial Correlation	.36*	.25	.29	.09
<i>Dosimeter between-frame variability</i> predictor factor				
Pearson Correlation	-.02	-.06	.09	.09
Spearman Correlation	-.04	-.15	.11	.05
Partial Correlation	-.01	-.06	.10	.09
<i>Dosimeter within-frame variability</i> predictor factor				
Pearson Correlation	.33*	.33*	.24	.03
Spearman Correlation	.36*	.31*	.28*	.08
Partial Correlation	.32*	.34*	.22	.04

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

correlations for the underlying fittings individually, and thus it is negatively correlated with advantage of *FAST-FAST* over *SLOW-SLOW* for speech intelligibility.

When considering Table 5 through 13, two general observations are noteworthy. Firstly, that the magnitude of the correlations between the nontraditional ecological, cognitive, and psychoacoustic factors and the benefit factors are of comparable magnitudes to those of the more traditional audiometric factors. Thus the influences are of comparable importance. Secondly, although the relationships that emerge are

statistically significant, there is still substantial residual unexplained variance. This is illustrated in Figure 1, which plots the additional benefit of the *FAST-FAST* compared to the *SLOW-SLOW* fitting for the *reported intelligibility* benefit factor against the *cognitive function* predictor factor. This example has been chosen because the magnitude of the correlation is amongst the strongest that emerge, and also because the relationship is novel and not available from more traditional audiometric data. Figure 1 shows that individual predictions based on the correlations will not be perfect, and that the

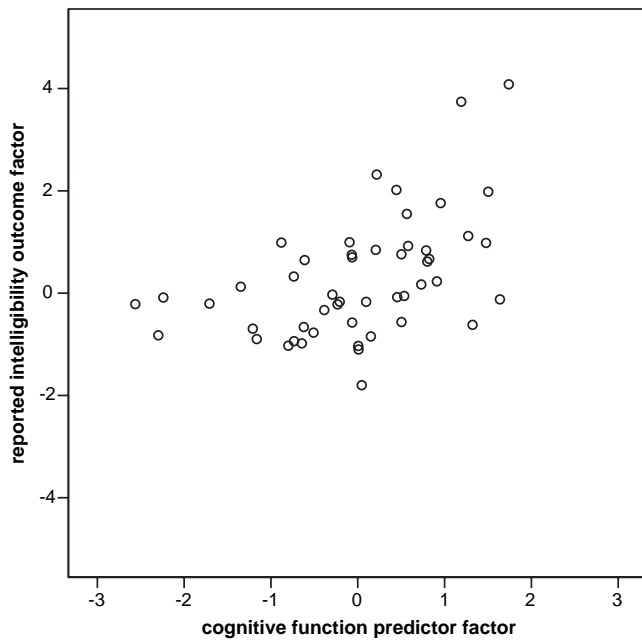


Figure 1. Scatterplot of the additional benefit of the *FAST-FAST* over *SLOW-SLOW* fitting against the *Cognitive Function* predictor factor for the *Reported Intelligibility* benefit factor.

requirement for fine-tuning following initial prescription will not be eliminated in a clinical implementation.

The use of derived factor scores for both outcome and predictor variables was designed to maximise the statistical leverage in the data, and the use of population standard deviation units (PSD) facilitated interpretation of effect sizes for the outcome variables. As an aid to interpretation of the predictive leverage in some common contributors to the predictor variables, Table 14 shows, for one single contrast (the advantage of the *FAST-FAST* fitting over the *LINEAR* fitting), the mean benefit factor scores broken down by:

1. audiogram slope;
2. difference in dynamic range between high and low frequencies; and

Table 14. Mean differences in the four benefit factors for the advantage of the *FAST-FAST* fitting over the linear fitting broken down by audiogram slope, differences in dynamic range and the raw score from the Auditory Lifestyle and Demand questionnaire, each of which is dichotomised at its median value. The table also shows the mean value of the break variable in each of the three sets of two subgroups

		<i>Listening Comfort benefit factor</i>	<i>Satisfaction benefit factor</i>	<i>Reported Intelligibility benefit factor</i>	<i>Speech Test benefit factor</i>
Audiogram slope	Group 1 (8.8 dB)	-.20	-.20	.15	-.13
	Group 2 (28.8 dB)	1.15	1.25	1.35	1.04
Difference in dynamic range (between low & high frequencies)	Group 1 (5.5 dB)	-.17	.21	.18	.24
	Group 2 (24.1 dB)	1.00	1.15	1.22	.85
ALD score	Group 1 (40.7)	-.50	-.18	-.27	.68
	Group 2 (59.0)	1.13	1.35	1.47	.45

3. the raw score from the Auditory Lifestyle and Demand questionnaire.

Each of these three variables dichotomised at its median value.

Discussion

The preceding analyses have shown that understanding the ways in which different listeners derive differing types and degrees of benefit from the linear and nonlinear fittings requires access to a diverse set of predictor variables. Greater benefits from the linear fittings were associated with audiometric profiles with flatter slopes, greater dynamic ranges, and smaller differences in dynamic range between higher and lower frequencies. In contrast, greater benefits from the nonlinear fittings were associated with more sloping losses, more reduced dynamic ranges and greater differences in dynamic range between higher and lower frequencies. Reports of auditory lifestyle and measures of the acoustic variability of listeners' environments showed that greater benefits from linear fittings are associated with less varied lifestyles and environments, while the opposite is the case for the three nonlinear fittings.

Greater benefits from slow-acting AVC were associated with greater *between-frame variability* (variation across different sections of the listening experience), whereas greater benefits for the fittings that contain fast-acting WDRC in the low-frequency channel were associated with greater *within-frame variability* (variation within sections of the listening experience).

Cognitive capacity links with the slow-acting AVC fitting and the fast-acting WDRC in different directions, so that listeners with greater cognitive capacity derived greater benefit from the fast WDRC fitting than slow AVC, whereas the reverse holds for lower cognitive capacity. If fast-acting WDRC is considered to offer increased moment-to-moment audibility at the expense of reduction in the information-carrying spectral and temporal contrast in speech, then one would suggest that for listeners with greater cognitive capacity, the benefits of increased audibility outweigh the penalties of reduced contrasts. Listeners with lesser cognitive capacities are unable to offset the penalties of reduced contrasts.

Turning now to associations between psychoacoustical consequences of SNHL and the benefits of different fittings, we

observe that those listeners who are more resistant to artificial degradations in the spectral and temporal cues in speech derived greater benefit from the *FAST-FAST* fitting. In contrast, a test of susceptibility to upward spread of masking (USOM) correlated with benefit from the *FAST-SLOW* fitting, though not for the *SLOW-SLOW* fitting, it should be noted. This lack of correlation for the *SLOW-SLOW* fitting suggests that a simple interpretation may not be a complete explanation for the apparent USOM association. The *FAST-SLOW* and *SLOW-SLOW* fittings implement the same static gain. The low (and high) frequency channels have the same attack-time, so the low-frequency channel of *FAST-SLOW* and *SLOW-SLOW* will undergo compression to the same degree following an increase in signal input. *FAST-SLOW* will (in the low-frequency channel) be released from compression more rapidly than *SLOW-SLOW*, so the low-frequency output of the *FAST-SLOW* fitting must always be greater than or equal to that of the *SLOW-SLOW* fitting. Thus listeners with greater susceptibility to USOM should also have derived greater benefit from the *SLOW-SLOW* fitting relative to *FAST-SLOW*; but this did not occur. One potential explanation of this anomaly might be that the test we constructed to measure susceptibility to USOM actually measures something other than, or in addition to, what was intended. The test measured the decrease in performance for high-pass filtered speech as low-frequency energy (noise) carrying the temporal envelope of the same speech low-pass filtered was increased. If listeners were able to use that low-pass envelope to support intelligibility, and that ability were to increase with increases in the low-pass level, then a decline in performance due to increased USOM could be attenuated. The putative test of susceptibility to USOM could have measured a composite of the original intent, but modulated by the audibility (and ability to use that audibility) of the low-frequency temporal envelope in speech. Thus what we have referred to as a *susceptibility to USOM* predictor factor may contain important influences from another psychoacoustic function. However no simple interpretation of the test can explain all of the pattern of results for the three nonlinear rationales given the positive correlation between the predictor factor and benefit from the *FAST-SLOW* fitting, and the absence of any significant positive or negative correlation elsewhere. Clarification via further experimentation has not been attempted.

While the pattern of correlations of the acoustic measures of within-frame and between-frame variability in relation to the objectives and characteristics of the linear and nonlinear fittings offer a ready interpretation, the time constants of the compressors and the time resolution of the acoustic measures are widely divergent. The release times are 40 ms and 640 ms, while the time resolution of the logged acoustic data is 10 s. It is not clear how different measures of variability derived from 10-second time slices might relate to the effects of compressor release times operating on a running speech signal at tens or hundreds of milliseconds. We can only suggest that the indices of between-frame and within-frame variability derived from 10-second resolution would covary with analogous indices derived across shorter timescales, and hence act as useable surrogates.

Despite some limitations in our ability to interpret the fine structure of some of the findings, a number of strong patterns do emerge. The *FAST-FAST* and *FAST-SLOW* fittings exhibit a

greater number and wider range of predictors than the *LINEAR* and *SLOW-SLOW* fittings. This results in a greater variance in the mean benefit scores for the WDRC fittings, with greater opportunities for relative benefits and penalties between fittings to emerge, and hence these fittings might be regarded as somehow 'less safe' than AVC or linear amplification. What is clear is the leverage provided by assessments of auditory ecology, cognitive capacity and the abnormal psychoacoustics of SNHL, both in differentiating between the linear and nonlinear fittings, and also between slow-acting AVC and fast-acting WDRC. Unfortunately, none of the items contributing to the Auditory Lifestyle and Demand Questionnaire are able to differentiate between-frame variability from within-frame variability, and clearly assessment of acoustic ecology prior to hearing aid fitting is not compatible with clinical reality. One might suggest though that hearing aid technology could itself contain the capacity to characterise the listener's acoustic ecology.

The results from this experiment are a clear indication that an appreciation of the diverse dimensions of hearing aid benefit, and the importance of auditory, ecological and cognitive influences on outcome is required for the comprehensive assessment of technological and fitting features. This finding will apply to both research and clinical practice settings.

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