ASPECTS OF AUDITORY ECOLOGY AND PSYCHOACOUSTIC FUNCTION AS DETERMINANTS OF BENEFITS FROM AND CANDIDATURE FOR NON-LINEAR PROCESSING IN HEARING AIDS

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INTRODUCTION

The technological flexibility of hearing aids, and their associated fitting rationales continue to increase, particularly with the advent into the market-place of digital devices enabling a wide range of signal-processing algorithms. Field trials of various hearing aids do suggest potential benefits to hearing-impaired listeners for a variety of processing schemes and their fitting, though these benefits may manifest themselves in different domains and, indeed, may be direct in tension. For example, an individual who requires to maximise speech intelligibility in-noise at all costs may be willing to accept a less than optimal fitting for speech intelligibility-in-more advantageous listening environments, and certainly a fitting which compromises overall listening comfort. Likewise, other listeners may prefer to maximise listening comfort at the expense of other dimensions of benefit and outcome, including speech intelligibility. Given the complexity of the issues, it would appear that no one processing or adjustment strategy achieves optimal performance or acceptance for all listeners with sensorineural hearing loss. There is a reasonable supposition that different listeners and different degrees and configurations of hearing impairment require different strategies. Furthermore, the non-linear distortions which are an almost inevitable accompaniment to sensorineural hearing impairment (such as reduced dynamic range, deficits in frequency and temporal processing etc.) suggest that there may be relationships between the detailed psychoacoustical characteristics of a hearing impairment and an optimal approach to hearing aid fitting. This inference can be drawn from the example that parameters of the hearing loss (e.g. slope, dynamic range) are associated with additional benefits from dual channel fast-acting wide dynamic range compression (Moore et al, 1992) and also from fast-acting compression in a low-frequency channel accompanied by slow-acting automatic volume control in a high-frequency channel, whose proclaimed rationale is to minimise spread of masking (Lunner et al, 1997). It remains a research challenge to identify those aspects of impaired psychoacoustical function in sensorineural hearing loss which predict candidature for marginal benefit from different processing and fitting algorithms.

The major objective of this article is to suggest another dimension of candidature that deserves attention. There is increasing recognition that aspects associated with hearing-impaired clients, including expectations, motivations, cognitive function and psychological approaches, might be influential in determining overall benefit and, further, might be related to differential candidature for signal-processing schemes. In addition, we now wish to put forward the hypothesis that the range, types and importance of the listening environments, within which hearing-impaired listeners are asked to function, can also be implicated in candidature. That is, the listening demands themselves can be influential. Thus, individuals who find themselves in a particular set or range of auditory environments asked to perform certain listening tasks, and the extent to which those listening tasks impinge upon their ability to fulfil lifestyle requirements, might be an important factor, independent of the characteristics of the impairment. We term this collection of attributes “auditory ecology” in an attempt to encapsulate the physical, environmental and listener-related aspects of the overall complex. The particular hypothesis that we wish to test is that listeners who are asked to function in a wider range or richer set of auditory environments are more likely to be candidates for amplitude compression fittings as opposed to straight-forward linear amplification.

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Amplitude compression can come in many forms and have many objectives (Dillon 1996). However, in almost all of its instantiations, one of the primary objectives is to maximise a listener's access to desired signals in as wide a range of auditory environments as possible. The objective in amplifying low-level sounds by amounts that are greater than higher level sounds is a simple example of such an approach. This paper draws on data from a partially-complete experiment from a wider programme concerning the benefits of and candidature for dual-channel amplitude compression systems to provide a preliminary test of the hypothesis. We characterise aspects of auditory ecology using questionnaires and electroacoustic instruments which provide a sampling of the auditory environment.

MATERIALS AND METHODS

Hearing Aid Fitting

The overall experiment takes established users of simple linear amplification from the United Kingdom National Health Service, and refits them using a research device produced by the Oticon Research Centre at Eriksholm (Naylor 1996). This device (known as JUMP-1) is a post-aural two-channel digital hearing aid with a seven-band filter bank, for which the gain-compression characteristics and time constants of the two compressor channels can be individually tailored. The overall experiment contains a number of contrasts and only a brief description is given here. One of the fittings the device to achieve the revised National Acoustic Laboratories' real-ear insertion gain formula for a 65 dB SPL input (Byrne and Dillon 1986) with output compression limiting adjusted to the 12 dB below the threshold of uncomfortable listening for sinusoids in each of the octave frequencies to account for loudness summation. A number of compression fittings are part of the experiment and include three fittings which differ only in their time constants. For each fitting, the amplitude compression characteristics are adjusted with a compression threshold of 50 dB SPL, and a compression ratio to achieve the predicted loudness from a threshold-based loudness model procedure (Elberling, 1999) designed to normalise loudness across frequency. As with the linear fitting, the maximum power output of the device is adjusted to be 12 dB below the threshold of uncomfortable listening for sinusoids at the octave frequencies. The three-time constants employed are (i) fast-acting wide dynamic range compression in both the low and high-frequency channels with time constants of 10 ms for the attack times and 40 ms for the release time in both channels (ii) a second combination uses slow-acting automatic volume control in both the high-frequency and low-frequency channels with attack times of 10 ms, and release times of 640 ms, and (iii) a third setting with fast-acting wide dynamic range compression in the low-frequency channel, and slow-acting automatic volume control in the high-frequency channel with the time constants as above. In the overall experiment there is a within-subject crossover design whereby each of the listeners experiences the NAL linear reference, and then a second linear reference and the three non-linear conditions in a randomised single blind manner to address some of the issues outlined in the introduction regarding psychoacoustic dimensions of candidature. For the restricted purposes of this paper, the details of the psychoacoustical tests are omitted, and we concentrate on auditory ecology. The full experiment will examine the extent to which and ways in which aspects of auditory ecology influence differential preference for the various non-linear fittings. The preliminary analyses in this paper contrast the NAL linear reference with the first of the non-linear fittings experienced in the cross-over design to maximise the available dataset. Thus the non-linear fittings reported here are heterogenous.

Fine Tuning

The application of the frequency-gain characteristic and compression ratio relies on a threshold based loudness model (Elberling, 1997) and standardised real-ear to coupler differences (Shaw & Vaillancourt, 1985). The latter are addressed using a first stage acoustic fine tuning procedure which uses the seven channel filterbank to adjust the delivered gain to the prescribed target for a 65 dB SPL speech-shaped noise input. Further patient based fine-tuning for speech in quiet and speech in noise at soft, conversational and loud speech levels, in addition to the listener's own voice, is employed to ensure acceptance by the listeners which might stem from individual departures from the predictions of the loudness model.

Listeners

The overall design calls for some sixty listeners in a 2 x 2 stratified design on the dimensions of impairment (dynamic range) and ecology (sparse vs. rich). All listeners have bilateral symmetric SNHL of moderate degree. To date, 29 listeners have progressed sufficiently through the experiment that they have completed the linear NAL arm of the testing, and at least one of the three non-linear fittings. Thus, in this paper, no attempt is made to investigate the benefits of or candidature for the different non-linear fittings in comparison to each other but, rather, any of the non-linear fittings in comparison to the linear reference. The air conduction hearing levels for the 29 listeners and the thresholds of uncomfortable listening are shown in Table I. The listeners, in general, exhibit sloping SNHL with a reduction in dynamic range at high compared to lower frequencies, but will contain samples of relatively flat impairments with more uniform dynamic range. Previous research has suggested that either a simple characterisation of audiogram slope, or the difference in dynamic range between high and low-frequencies might be influential in candidature for amplitude compression systems. Accordingly, two summary indices were derived. Firstly, the slope was characterised as the difference between mean thresholds at 2000 and 4000 Hz and those at 500 and 1000 Hz expressed in dB per octave, and secondly the difference in dynamic range between low and high-frequencies was similarly constructed. These values are shown in Table II.

Outcome measures

The comprehensive experiment contains a series of speech identification-in-noise procedures for a variety of speech input levels, noise input levels, and interfering noise types. These will be the primary outcome measures when attempting to determine the ways in which psychoacoustical aspects of sensorineural hearing impairment influence candidature for and benefit from the processing options in the performance domain. For this paper, we wish to concentrate on the perceived benefits of and preferences for the different systems and, therefore report data from a variety of self-report measures. Individuals completed the Glasgow Hearing Aid Benefit Profile (Gatehouse 1999) for each of these fitting, the Abbreviated Profile of Hearing Aid Benefit (Cox and Alexander 1995), the Satisfaction with Amplification in Daily Life (Cox and Alexander 1997) and direct scales for rating the overall impression of the hearing aid, and separate ratings of speech clarity and listening comfort (Hagerman and Gabrielsson 1985). Each of these individual data points was transformed to a z-score and an overall composite score for each of the fittings derived by simple unweighted addition. Clearly, such a procedure can disguise effects which may occur in only one or other of the outcome measures, and might be an insensitive approach. However, at this preliminary stage of the data analysis, it is felt that such a method is robust in that it is unlikely to identify idiosyncratic effects that are peculiar to a particular questionnaire or other self-report instrument. The primary intention of this paper is to investigate the influence of auditory ecology at a more general level.

Assessment of auditory ecology

Two approaches were taken to gain access to aspects of auditory ecology. Firstly, a questionnaire was developed which presents each of the listeners with 24 types of listening circumstance, and asks them to rate on a 3 point scale the extent to which those listening circumstances occur in their everyday life. Additionally, for each of the circumstances, listeners rate on a 3-point scale the importance of that listening circumstance to their everyday experience and demands. The 24 everyday circumstances that make up the Auditory Lifestyle and Demand questionnaire are shown in Table III. The objective of the questionnaire is to characterise the richness of the auditory lifestyle and environments that different listeners are required to function in, and to further examine their relative contribution to everyday function via ascertainment of individual importance. Thus we attempt to access richness/diversity and importance. Two indices are derived from the Auditory Lifestyle and Demand questionnaire. The first of these accesses only the frequency of occurrence data and is scaled so that responses might theoretically span from 0-100 arbitrary units. The second index weights each individual frequency data point by the importance of that circumstance to the listener's lifestyle in a simple linear manner, and is again scaled to theoretically span the range of 0-100 arbitrary units. In both cases, larger values represent a "richer" auditory lifestyle.

The second approach to characterisation of auditory ecology uses electroacoustic environmental logging devices which have been developed for monitoring of workplace noise levels. These use a commercially-available instrument (QUEST Q-400 Noise Dosimeter) which is used to log the A-weighted sound pressure level over a 10 sec epoch into an internal memory. The average SPL for each 10 sec epoch is ascertained, and the device contains sufficient internal memory for logging of each 10 sec epoch between 6 a.m. and midnight. Listeners wore these logging dosimeters for a 7-day period during the course of which they reported no abnormal life activities (i.e. a "typical" week). Listeners were supplied with the dosimeters and the data were down-loaded to a personal computer on a daily basis for later analysis. There are a number of ways of characterising the distribution of sound levels available and two indices are reported in the presentation of this article. One of the essential aims of the research is to identify which methods have maximum utility. This communication uses an initial simple approach on a restricted data set.

Listeners completed a diary during the course of each day. Having selected the monitoring periods for each day reported by each listener as being between waking up and retiring to bed the simplest index of range of environmental levels is the simple standard deviation of the measured levels – referred to hereafter as the "SPL Standard Deviation". One objective of an amplitude compression regime is to remove from the listener the need to make adjustments to any volume control on a hearing aid. Our second approach computes the standard deviation over a 10 minute interval, increments the sample window by one 10 second epoch and recomputes. The index is the average of all of these computations, and is a first attempt at a characterisation of a lifestyle factor for which audiometric amplitude compression systems may be designed to provide appropriate adjustment. In general terms this second index represents the range of levels encountered during a time period (arbitrarily set at 10 minutes) when the listener might reasonably expect not to have to make adjustments to the device. This index is referred to hereafter as "SPL running standard deviation".

RESULTS

Figure 1 shows the distribution of composite preferences aggregated over the various self-report outcome measures for some form of non-linear processing over linear processing. The graph shows the strength of the preference with a positive value representing preference for non-linear processing and a negative value representing preference for linear processing. 20 of the 29 listeners expressed an overall preference for non-linear processing and nine for the linear fitting. From the point of view of practical application, the likely relevant outcome is whether the expressed preference is for linear or non-linear whilst, from a perspective of scientific understanding and the investigation of the role of predictors, the most appropriate outcome measure may be the strength of that preference as opposed to the simple binary classification. Throughout this article, both outcomes are used in the analyses as both of the objectives have potential relevance.

Table IV shows the correlation coefficients and associated significance levels between the two dependent variables (preference and strength of that preference) and a variety of potential predictors. In the case of the binary preference variable, the values are bi-serial correlation coefficients, while in the case of the strength of preference the values are product moment correlations. For the binary outcome of preference, there are significant correlations with audiogram slope, difference in dynamic range, the SPL running standard deviation from the noise monitoring and the raw score from the Auditory Lifestyle and Demand questionnaire. For the strength of preference, there is a significant correlation with the SPL running standard deviation while the other predictors do not achieve statistical significance at $p<0.05$. Given that the Auditory Lifestyle and Demand questionnaire and the environmental monitoring both aim to act as characterisation of auditory ecology, it is instructive to examine the relationship between the various measures from these sources. The product moment correlations and associated significance levels are shown in Table V and it can be seen that there are significant correlations between the SPL running standard deviation (but not the overall standard deviation) and both of the scores from the Auditory Lifestyle and Demand Questionnaire.
While the correlation coefficients in Table IV are informative, it is not clear whether the significant correlations are expressions of covariance amongst the potential predictors, or whether the predictors exhibit independent leverage. Therefore a pair of multivariate analyses were performed using a logistic regression procedure when binary preference is the dependent variable and linear regression procedure when the strength of preference is the dependent variable. The results are summarised in Tables VI and VII respectively. When binary preference is the dependent variable, there are significant independent contributions from difference in dynamic range at the low and high frequencies, the SPL running standard deviation from the environmental monitoring, and the raw (not weighted by importance) score from the Auditory Lifestyle and Demand questionnaire, which account for 32%, 10.2% and 7.8% of the variance respectively. When the strength of preference is the dependent variable, there are significant contributions from the SPL running standard deviation and the importance weighted score from the Auditory Lifestyle and Demand questionnaire accounting for 32.4% and 7.2% of the variance respectively. Thus, the data replicate previous findings concerning the relationships between configuration of the impairment and binary preference, but show that even when this is controlled for in a multivariate procedure, there are additional significant contributions from aspects of auditory ecology as accessed by both the electroacoustic measures from environmental monitoring and the self-report measures from the Auditory Lifestyle and Demand Questionnare. In contrast, the strength of preference for non-linear as opposed to linear processing does not have an independent contribution of audiogram configuration but is significantly influenced by both of the characterisations of auditory ecology from the electroacoustic measures and the self-report questionnaire. Thus the data support the contention that (independent of characteristics of the sensorineural hearing impairment) aspects of auditory ecology do significantly relate to the preference and the extent of preference for non-linear as opposed to linear processing. The direction of the effect is such that individuals who experience more rich and diverse lifestyles

more often express a preference and express a stronger preference for the non-linear processing elements.

DISCUSSION

The findings in this article can be used to support the hypothesis that, in addition to established roles for auditory impairment and psychophysical characteristics of sensorineural hearing loss, there are potential contributions to the ways in which listeners will select appropriate processing for a hearing aid which relate not to any aspects of their auditory system but rather to the environments that their impaired auditory system is asked to function in, the demands that are placed upon their auditory system when in those environments, and the importance of those demands to every day living. We have used the term "auditory ecology" to encapsulate this effect and this would appear appropriate, given the dictionary definition of "study of interaction of persons with their environment" in the widest sense. The context within which the current findings have been gathered, however, do place a number of restrictions on their interpretation and potential generality. The Auditory Lifestyle and Demand questionnaire is a prototype instrument whose overall validity and applicability remains to be established. Certainly the questionnaire can by no means be regarded as optimised for its current purpose. It may well be that particular leverage is exerted by subsets of the current 24 questions which might provide more informative relationships between eventual preferences and strengths of preferences. Similarly, the current environmental monitoring merely logs the A-weighted sound pressure level over an epoch and no attempt has been made to link the electroacoustic measures to the particular activities as noted in the diaries other than selecting time periods when the listeners were not asleep. It will be informative in the future to relate the data from the Auditory Lifestyle and Demand questionnaire to the individual diaries and to make more sophisticated the electroacoustic data that is acquired by accessing aspects of the input spectrum and classifications of the type of input signal (e.g. speech versus non-speech) in addition to a simple characterisation of overall level. Despite these limitations, we suggest that the current results are encouraging in that the current rather unsophisticated characterisations of auditory ecology in both the electroacoustic and the self-report domains show interpretable patterns of relationships with eventual preferences and strength of preference. In a similar vein, we argue that the use of a composite preference and strength of preference using a variety of self-report instruments also points to the robust nature of the relationships that we have identified. It will be instructive to probe the ways in which and extent to which different outcome measures reveal the relationships to greater or lesser extent, both from the point of view of providing more analytically informative information, but also as a method of learning more about the outcome measures themselves.

One potentially important way in which the non-linear fittings differ from the NAL reference is that only the latter has access to a user-adjustable volume control. Thus the expressed preferences might be contaminated by individuals' reaction to this difference. The influence of ecology is still relevant to the comparison, though more information will be available from further conditions in the experiment which control for this access.

As indicated in the Methods section of this article, the current results arise from a subset of a wider experiment from which it will be possible to determine the extent to which the findings generalise to larger groups of listeners with sensorineural hearing loss. Furthermore, when the balanced cross-over design is complete, it will be possible to analyse the non-linear regimes separately to discern whether the relationships exist across all types of non-linear processing or whether there are specific patterns within different non-linear regimes with their different underlying conceptual rationales. Furthermore, coupling the current approach with aspects of psychoacoustical function in the loudness, frequency and temporal domains will provide the opportunity to investigate the ways in which performance on speech identification procedures in the different fittings and preferences for those fittings might relate to psychoacoustical and ecological characteristics of the listeners and other potential predictors such as cognitive abilities.

CONCLUSION

Given the objectives and types of amplitude compression systems in hearing aids, a logical hypothesis is constructed for the role of aspects of auditory ecology in preferences and strengths of those preferences for non-linear processing as opposed to an appropriate linear reference. Data from a self-report questionnaire and electroacoustic measures of the environment support this contention. We contend that a comprehensive approach to the benefits of hearing aids and candidature for the various processing options within hearing aids should hereafter access not only predictors in the domain of impairment characterisation but should take account of the environments, demands and importance of those aspects to individual lifestyles. A holistic approach to hearing aid fitting and candidature which includes aspects of auditory ecology can help to identify those types of signal processing and hearing aid adjustments that will lead to greater acceptance and delivered benefit to hearing impaired listeners.

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Table I Mean (and standard deviation) of air conduction hearing levels and thresholds of uncomfortable listening for the 29 listeners

	Frequency Hz			
	500	**1000**	**2000**	**4000**
Air conduction thresholds dB HL	32.4 (8.1)	37.2 (8.3)	49.3 (9.3)	64.1 (6.4)
Threshold of uncomfortable listening dB HL	104.0 (9.9)	105.9 (7.9)	109.5 (7.9)	112.6 (9.4)

Table II Derived audiometric parameters

	Mean	**Standard deviation**
Audiogram slope dB/Oct	11.0	4.2
Difference in dynamic range dB/Oct	7.9	4.2

Table III Items used in the Auditory Lifestyle Demand Questionnaire

1. Listening in a background of noise
2. Listening to sounds that are quiet and difficult to hear
3. Listening to sounds that are consistently loud
4. Listening to things that are close by you
5. Listening to things that are far away
6. Listening when there are lots of echoes
7. Listening when two or more people are talking at once
8. Having to listen to sounds that vary a lot in loudness
9. Talking on the telephone
10. Listening to music at home
11. Listening to music at a concert
12. Listening to the radio
13. Listening to the television
14. Listening to sounds or voices that are moving around
15. Listening when you have no control or influence over the speaker
16. Listening when not being able to understand could be embarrassing
17. Listening when misunderstanding could cause an accident
18. Listening when misunderstanding could cause you to lose money
19. Listening to a speaker who is in another room
20. Listening to a speaker whose voice is not familiar to you
21. Listening to the sounds of nature
22. Having to understand what is happening around you
23. Listening to people with unfamiliar accents or dialects
24. Being in a situation where you actually do not want to hear what is happening (for example, intrusive background noises)

Table IV Correlation coefficients between Preference and Strength of preference for non-linear vs linear processing with the audiometric summary indices, indices from the environmental monitoring and scores from the auditory lifestyle and demand questionnaire

	Preference	**Strength of preference**
Audiogram slope	0.45*	0.21
Difference in dynamic range	0.59**	0.34
SPL standard deviation	-0.09	0.24
SPL running standard deviation	0.51**	0.59**
ALD Score	0.38*	0.21
ALD Score (Importance weighted)	0.25	0.03

*p<0.05 **p<0.01

Table V Correlation coefficients between the scores from the Auditory Lifestyle and Demand questionnaire and the indices from the environmental monitoring

	SPL Standard Deviation	**SPL Running Standard Deviation**
ALD Score	-0.01	0.56**
ALD Score (Importance weighted)	0.03	0.46**

*p<0.05 **p<0.01

Table VI Summary of the stepwise logistic regression using Preference as the dependent variable

Variable Entered	**% Variance Explained**	**Significance Level**
Difference in dynamic range	32.0%	p<0.001
SPL Running Standard Deviation	10.2%	p<0.05
ALD Score	7.8%	p<0.05

Table VII Summary of the stepwise linear regression using Strengths of Preference as the dependent variable

Variable Entered	**% Variance Explained**	**Significance Level**
SPL Running Standard Deviation	32.4%	p<0.001
ALD Score (Importance weighted)	7.2%	p<0.05

Figure 1 Histogram showing strengths of preference for non-linear over linear processing