ADAPTIVE DYNAMIC RANGE OPTIMISATION FOR HEARING AIDS

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ABSTRACT – ADRO (Adaptive Dynamic Range Optimisation) is a slowly-adapting digital signal processor that controls the output levels of a set of narrow frequency bands so that the levels fall within a specified dynamic range. ADRO is suitable for a variety of applications, including control of a hearing aid. In the case of a hearing aid, the output dynamic range is defined by the threshold of hearing (T) and a comfortable level (C) at each frequency for the individual listener. A set of rules is used to control the output levels, with each rule directly addressing a requirement for a functional hearing aid. For example, the audibility rule specifies that the output level should be greater than a fixed level between T and C at least 70% of the time. The discomfort rule specifies that the output level should be below C at least 90% of the time. In this study, open-set sentence perception scores for 15 listeners were compared for ADRO and a linear hearing aid fit. Speech was presented at three levels. ADRO improved scores by 1.9% at 75 dB SPL (NS), 15.9% at 65 dB SPL ($p = 0.014$) and 36% at 55 dB SPL ($p < 0.001$).

INTRODUCTION

The main problem resulting from hearing impairment in adults is poor audibility of sounds at normal intensities. This problem may be overcome to some extent by amplifying sounds with a hearing aid, however amplification can introduce further problems. The loudness of sounds often grows faster than normal in hearing-impaired ears (recruitment), so that loud sounds may become uncomfortable after they are amplified by the hearing aid. Often, hearing thresholds and maximum comfortable levels vary with frequency so that the gain of the hearing aid needs to change as a function of both frequency and intensity of the input signal to provide an output signal that is both audible and comfortable. Linear hearing aids attempt to meet the audibility criterion with a fixed gain and frequency response such that speech signals at a normal intensity are placed near the middle of the listener's range of hearing. The National Acoustics Laboratory (NAL) prescription is a widely used example (Byrne & Dillon, 1986; Byrne, Parkinson & Newall, 1990). Linear hearing aids usually incorporate a maximum power output limiter to meet the comfort criterion. Clearly, a linear aid with limiting can only provide a good approximation to the required gain as a function of frequency for a fairly narrow range of input levels. The NAL non-linear prescription (NAL-NL1, 1999) provides a more detailed description of the required gain function, together with recommendations for implementations using single- and multi-band compression hearing aids. Most alternative hearing aid prescriptions take a similar form: i.e. they specify the required gain as a function of the input frequency and intensity parameters (Skinner, 1988).

ADRO is designed to take a more direct approach by specifying target output levels as a function of frequency in such a way that the audibility and comfort criteria are met automatically. The gain of the hearing aid is adapted in order to keep the output signal level within the optimum dynamic range. These target output levels are related to measured threshold and comfortable levels in a more straight-forward manner than the gain parameters specified in other types of processors.

The aim of this study was to validate the ADRO processing and fitting procedure for a range of hearing-impaired listeners. The hypothesis was that ADRO would produce higher speech perception scores than a standard fixed-gain hearing aid, especially at moderately low presentation levels where the additional gain provided by ADRO should improve audibility.

METHOD

Statistical description of the output signal

The first requirement for ADRO is to measure the distribution of output levels as a function of frequency and time. To achieve this goal, the ADRO processor uses a 128 point Discrete Fourier Transform (DFT) to split the sampled input signal into 64 frequency bins, F_i. A Hanning window is applied prior to the DFT. The complex input amplitude, I_i, of each frequency component is multiplied by a scalar gain factor, G_i, to obtain the output amplitude, O_i. ADRO uses estimates of the distribution of output levels in the form of percentiles. For example, the 90th percentile is the level which is exceeded 10% of the time, and the 50th percentile is the level that is exceeded 50% of the time. These percentiles are estimated by comparing the magnitude of the output amplitude, $|O_i|$, with the current value of the percentile estimate. If the magnitude is greater, the estimate is increased by a small amount, U dB. If the magnitude is smaller than the estimate, then the estimate is reduced by a small amount, D dB. If U and D are equal, then the estimate will tend to the 50th percentile because the number of upward steps will then be equal to the number of downward steps. Other percentiles may be estimated by changing the relative size of U and D. The percentile value is given by 100 U/(U+D). For example, if U is 9 times larger than D, one upward step will be balanced by 9 downward steps, and the estimator will tend to the 90th percentile where the probability of a downward step is 9 times greater than the probability of an upward step. The rate at which the percentile estimates change is controlled by the absolute size of U and D, and the frequency with which the FFT windows are updated. Typically, the slew rate for the estimates in ADRO is about 20 dB per second.

The ADRO targets for a hearing aid user

The second requirement for ADRO is to measure, or define, the required output dynamic range for each of the frequency bands. For a hearing aid user, the limits of the useable dynamic range are the threshold of hearing and the maximum comfortable level, MCL, for each frequency. These parameters are measured using 1/3 octave bands of noise covering the frequency range of interest. These signals are generated by the ADRO processor itself, controlled by a PC program called AUDY. The target output levels for ADRO are derived from threshold and loudness estimates. Thresholds, T_i, are measured using a conventional adaptive detection procedure. Following the threshold measures, a 7-point loudness scale (Hawkins et al, 1987) is used to establish the dynamic range. The 7 categories are: very soft, soft, comfortable but slightly soft, comfortable, comfortable but slightly loud, loud but OK, uncomfortably loud. ADRO uses three target levels at each frequency: M_i, C_i, and A_i, which represent the maximum output level, a comfortable level, and a minimum audibility level at each frequency. The "loud but OK" level is used for M_i, the "comfortable" level is used for C_i, and the A_i level is either C_i-20 dB or T_i, whichever is greater.

The ADRO rules

ADRO uses a set of rules that are applied independently at each frequency: The comfort rule requires the 90th percentile to be below the C_i target level for every frequency. If the comfort rule is violated, the gain, G_i, at that frequency is reduced by a small amount. The audibility rule requires the 70th percentile to be above the A_i target for every frequency. The audibility rule is checked only if the comfort rule is satisfied. If the audibility rule is violated, the gain, G_i, is increased by a small amount. The sizes of the increments and decrements of gain are chosen so that the maximum rate of decrease is about 9 dB per second, and the maximum rate of increase is about 3 dB per second. In a more conventional automatic gain control, these parameters would be equivalent to very long attack and release times. The maximum gain rule requires the gain to be less than a fixed amount $Gmax_i$. This rule limits the loudness of background noise and avoids feedback in quiet situations where the gain might otherwise become very high. A typical value of $Gmax_i$ for profoundly deaf listeners would be about 60 dB. Finally, the maximum output rule requires the magnitude of the output level, $|O_i|$, to be less than M_i. If this rule is violated, the magnitude of O_i is reduced to be equal to M_i, leaving its phase unchanged. The final stages of processing are to apply an inverse DFT to the amplified output levels O_i, multiply the result with a Hanning window, and use the overlap/add method to generate an output signal. A final multiplier is incorporated to give the listener control of the overall loudness. Usually, this volume control is set to attenuate the signal. This attenuation is most likely required to compensate for intensity and loudness summation across the frequency bands, each of which is capable of reaching a loud level on its own. In other words, the thresholds and comfortable levels of broad-band signals like speech are lower than the corresponding values for narrow-band noise.

The ADRO hearing aid

The ADRO hearing aid used in this study was a benchtop processor based on a Motorola DSP 56303 digital signal processor evaluation board, fitted with a microphone, preamplifier, output amplifier and an Oticon AN180, AN270, or AP1000 hearing aid receiver which was attached to an individually fitted hearing aid mould for each listener. The hearing aid receiver model was chosen according to the output power required for each listener. The sampling rate of the analog to digital converter was 9.6 kHz, giving a window length of 13.3 ms. Overlapping windows of data were analysed every 3.3 ms. The Motorola processor was interfaced to a personal computer running Windows 95 via a serial port so that the AUDY program could control the stimulus generation and parameter selection during the fitting procedure. The AUDY program could also be used to display a snapshot of the percentile estimates, output levels, and gains at about 1 second intervals. This display was useful to verify and explain the operation of the ADRO rules. It was also possible to implement a fixed-gain hearing aid by disabling the adaptive operation of the ADRO rules and setting the G_i values according to the NAL-RP prescription (Byrne et al, 1990). An upper limit to the $|O_i|$ values was implemented in a frequency-specific manner as for ADRO.

Participants and procedures

Fifteen adults with moderate to profound hearing loss (44 to 98 dB HL pure-tone-average hearing loss) took part in this study. All but two of the participants normally used a hearing aid. Results for the two participants who did not normally use hearing aids may be identified in Figures 1 to 3 by their hearing losses of 60 and 78 dB HL. The audiogram for each participant was measured using standard audiological procedures and equipment, and a NAL-RP prescription hearing aid was programmed. The ADRO hearing aid targets were determined for each individual using the loudness estimation procedure described above. The speech perception of each participant was tested with each of the 2 processors at free-field intensity levels of 55, 65, and 75 dB SPL using open-set CUNY sentences (Boothroyd, Hanin, & Hnath, 1985). The CUNY sentences were recorded onto CD by a female Australian speaker and the RMS levels of individual sentences were equalised digitally prior to presentation. The list numbers used for different conditions were randomised and no participant was tested more than once with the same list. Each sentence list contains 102 words, and was scored according to the percentage of words correctly repeated. Prior to the speech perception testing, the volume setting of the NAL hearing aid was adjusted to match the loudness of speech at a normal conversational level for both aids.

RESULTS

The scores for the individual participants at the three presentation levels are shown in Figures 1 to 3. Three of the participants had insufficient time available to complete the testing and scores were not obtained at 75 dB SPL for two participants and at 55 dB SPL for 1 participant. A two-way ANOVA indicated that presentation level, hearing aid, and the interaction term were all significant with $p < 0.001$. F values were 111.02, 42.06, and 12.58 respectively. The mean scores for NAL and ADRO hearing aids at 75 dB SPL were 83.6% and 81.7%, respectively. The difference of 1.9% was not statistically significant (post hoc Tukey t-test, $t = 0.38$, $p = 0.99$). At 65 dB SPL, mean scores were 79.6% for ADRO and 63.7% for NAL. The mean difference of 15.9% was significant ($t = 3.42$, $p = 0.014$). At 55 dB SPL, the mean scores were 55.0% and 18.6% and the difference of 36.4% was highly significant ($t = 7.56$, $p < 0.001$).

The mean scores at different presentation levels were also compared using post hoc Tukey t-tests. The mean scores at 65 and 75 dB SPL for ADRO were not significantly different (difference = 6.1%, $t = 1.28$, $p = 0.80$), but the scores at 55 dB SPL were significantly lower than at 65 dB SPL (difference = 27.1%, $t = 5.71$, $p < 0.001$). For the NAL prescription, the mean score at 65 dB SPL was lower than at 75 dB SPL (difference = 20.2%, $t = 4.15$, $p = 0.001$), and the mean score at 55 dB SPL was lower than at 65 dB SPL (difference = 47.6%, $t = 10.02$, $p < 0.001$). These results indicate that ADRO maintains maximum intelligibility at lower intensities than the NAL prescription hearing aid.

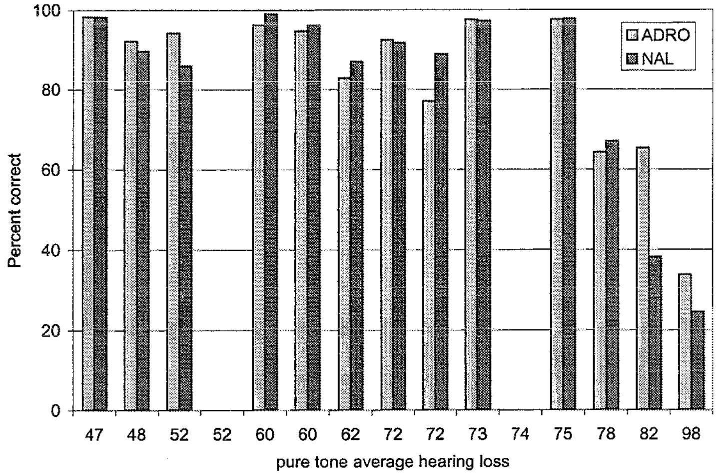

Figure 1. Comparison of open-set sentence perception scores at 75 dB SPL for 13 subjects using ADRO and a NAL linear hearing aid fit. Scores for individual subjects are ordered by increasing hearing loss in dB HL. The mean difference was 1.9%.

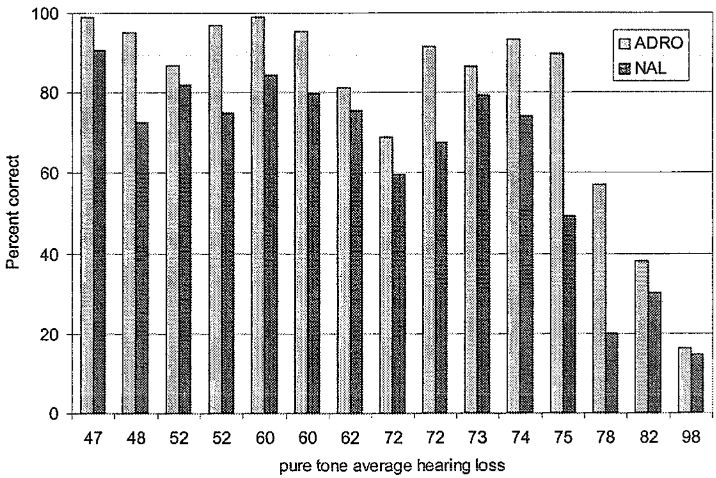

Figure 2. Comparison of open-set sentence perception scores at 65 dB SPL for 15 subjects using ADRO and a NAL linear hearing aid fit. Scores for individual subjects are ordered by increasing hearing loss in dB HL. The mean difference was 15.9%.

DISCUSSION

The hypothesis was supported by the group results at 55 and 65 dB SPL. At 75 dB SPL, ADRO was no worse than the NAL prescription. These intensity levels correspond to speech at levels described as "casual", "raised", and "loud" (Keidser, 1995; Pearsons et al, 1977). It should be noted that the recordings were made at a "normal" level (60 dB SPL) and then adjusted to the presentation levels, rather than recording "casual", "raised" and "loud" speech which would have resulted in different spectral shapes for the three conditions. The results indicate that ADRO should provide a significant advantage in most common situations at normal conversational levels. At 75 dB SPL, most participants showed little difference between the NAL and ADRO scores which were both quite high (over 80%). These differences may have been restricted by a ceiling effect. The largest difference at 75 dB SPL occurred for a subject with a severe hearing loss (PTA = 82 dB HL) where there was no ceiling effect because both scores were lower. At 65 and 55 dB SPL, every participant scored at least a little higher with ADRO than with NAL. At 65 and 75 dB, the largest improvements were for participants with severe hearing losses over 75 dB HL. At 55 dB SPL, this trend was reversed and the largest improvements were for participants with moderate and severe hearing losses less than 75 dB HL

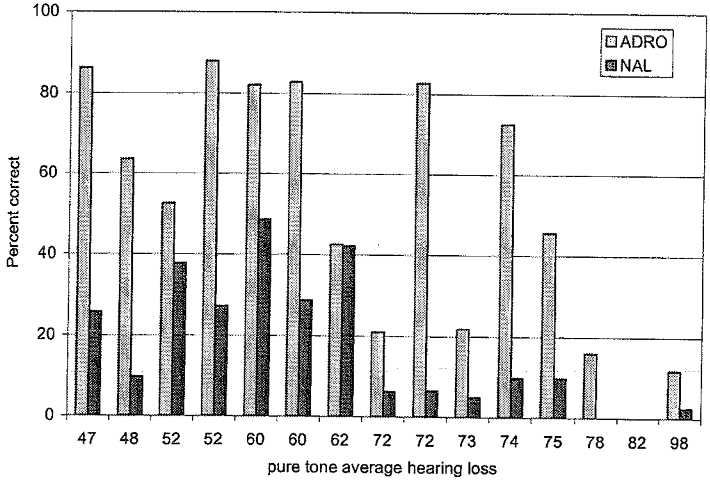

Figure 3. Comparison of open-set sentence perception scores at 55 dB SPL for 14 subjects using ADRO and a NAL linear hearing aid fit. Scores for individual subjects are ordered by increasing hearing loss in dB HL. The mean difference was 36.4%.

Further research is needed to evaluate the ADRO hearing aid with different materials and under different conditions. It remains to demonstrate that ADRO can protect listeners from the discomfort of loud sounds, both speech and environmental. An evaluation with more difficult materials may possibly indicate an advantage at 75 dB SPL if the present results are indeed limited by a ceiling effect. The present study does not indicate the relative performance of ADRO and NAL hearing aids in background noise. Background noise is a major problem for hearing aid users, and it is possible that ADRO may exacerbate this problem by amplifying the noise to louder levels. These additional issues have been addressed for the application of ADRO to the commercially available SPRINT cochlear implant speech processor (Blamey, James, & Martin, 1999). With SPRINT, a significant advantage was found for ADRO at high input levels for monosyllabic words but not for CUNY sentences, an advantage was found for ADRO at moderate and low input levels for both monosyllabic words and CUNY sentences, and ADRO performed no worse than the standard processor in background noise. A questionnaire established that implant users preferred the ADRO processor over the standard processor in 53% of common situations, compared with no preference in 32% and a preference for the standard processor in 10% of situations. Indiscriminate generalisations should not be made from cochlear implants to hearing aids, but it seems probable that the results will also be good when ADRO has been implemented in a wearable hearing aid.

There are commercially available hearing aids that include various forms of automatic gain control or compression (reviewed by Dillon, 1996) that may perform as well as ADRO in quiet at different presentation levels. Further studies will be conducted to compare ADRO with a commercially available compression aid.

CONCLUSIONS

The concept of adaptive dynamic range optimisation (ADRO) potentially provides a straight-forward solution for some of the most pervasive problems faced by people with impaired hearing. This study demonstrated clearly that ADRO provides a good solution to the problem of poor audibility of speech over a broader range of input levels than a conventional fixed-gain hearing aid. It remains to be shown that the ADRO hearing aid provides a solution to the other two major problems of discomfort in loud noises and poor intelligibility of speech in background noise.

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