ACTIVE NOISE CONTROL COMMUNICATION HEADSETS FOR THE ENTERTAINMENT INDUSTRY

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Executive Summary

This literature review was produced at the request of SHAPE, the association for Safety and Health in Arts Productions and Entertainment.

SHAPE asked us to provide information on state of the art techniques in reducing noise exposure.

We conducted a systematic and comprehensive review of the scientific literature with respect to two methods: (1) controlling noise exposure, via active noise control headsets (the subject of this report) and (2) reducing hearing damage, via pharmaceutical interventions (the subject of a short report titled "*Drug* T*reatments for Hearing Loss*", which follows).

Active noise control (ANC) headsets are very similar to regular communication except that they have built in active noise control systems that reduce the amount of ambient (unwanted) noise. In an ANC headset, a small microphone on the outside of the headset picks up the unwanted, external noise, and instantaneously emits a counter-signal that cancels it out, leaving only the desired communication signal.

ANC devices are primarily used today by aircraft pilots. However they have been tested in other occupations characterized by high levels of background noise and the need for accurate communication. These devices may be able to reduce the ambient noise in entertainment work environment, thus increasing speech intelligibility, and potentially lowering damaging noise at the ear.

This report provides a technical background to the concept of active noise control, discusses its use in the entertainment industry and provides guidance on how to select the appropriate device.

Table of Contents

Introduction

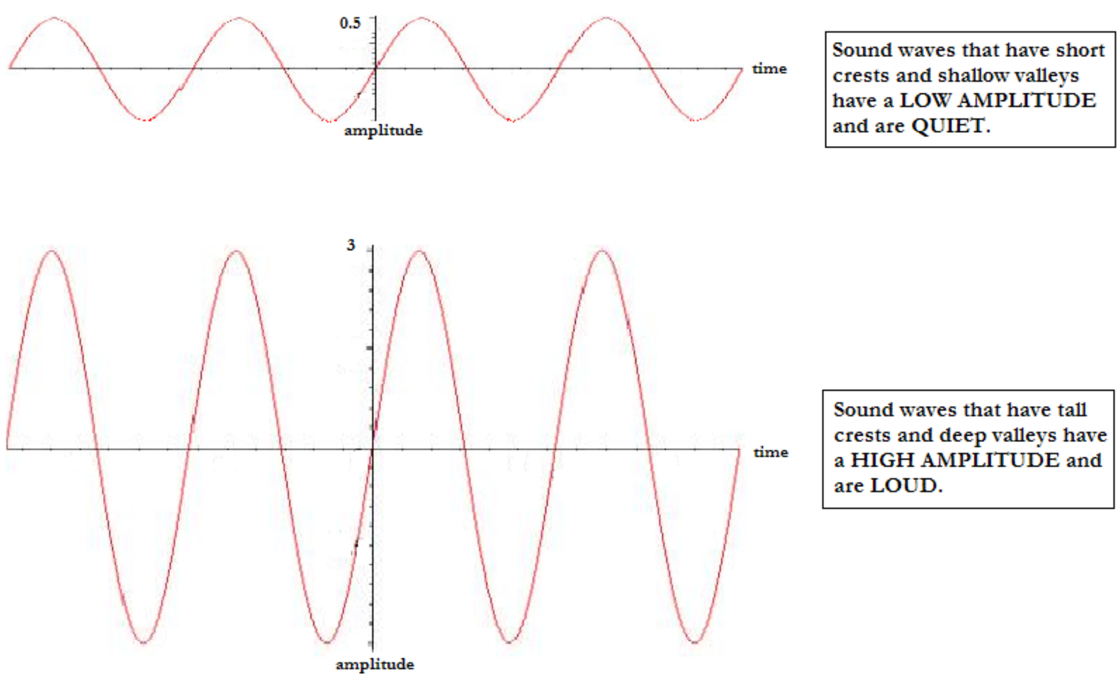
Is your current communication headset not working out for you? Do you find yourself raising the volume on your headset in order to hear the person with whom you are trying to communicate? Then, perhaps you will find this report useful. It describes active noise control and how it is currently being used in headsets to reduce the ambient noise from your surroundings, enabling you to lower the volume on your headset, reducing your noise exposure from your ambient surroundings and from the headset itself, and lowering your risk for developing noise-induced hearing loss. By the end of this report, you should understand the principle behind active noise control and how it is being employed in communication headsets. You will then be able to make an informed decision, based on your type of noise exposure, about whether an active noise control headset is right for you, and which type might be best for your work situation.

What is active noise control?

In order to understand how an active noise control communication headset may be useful it is first necessary to explain what active noise control is and how it works.

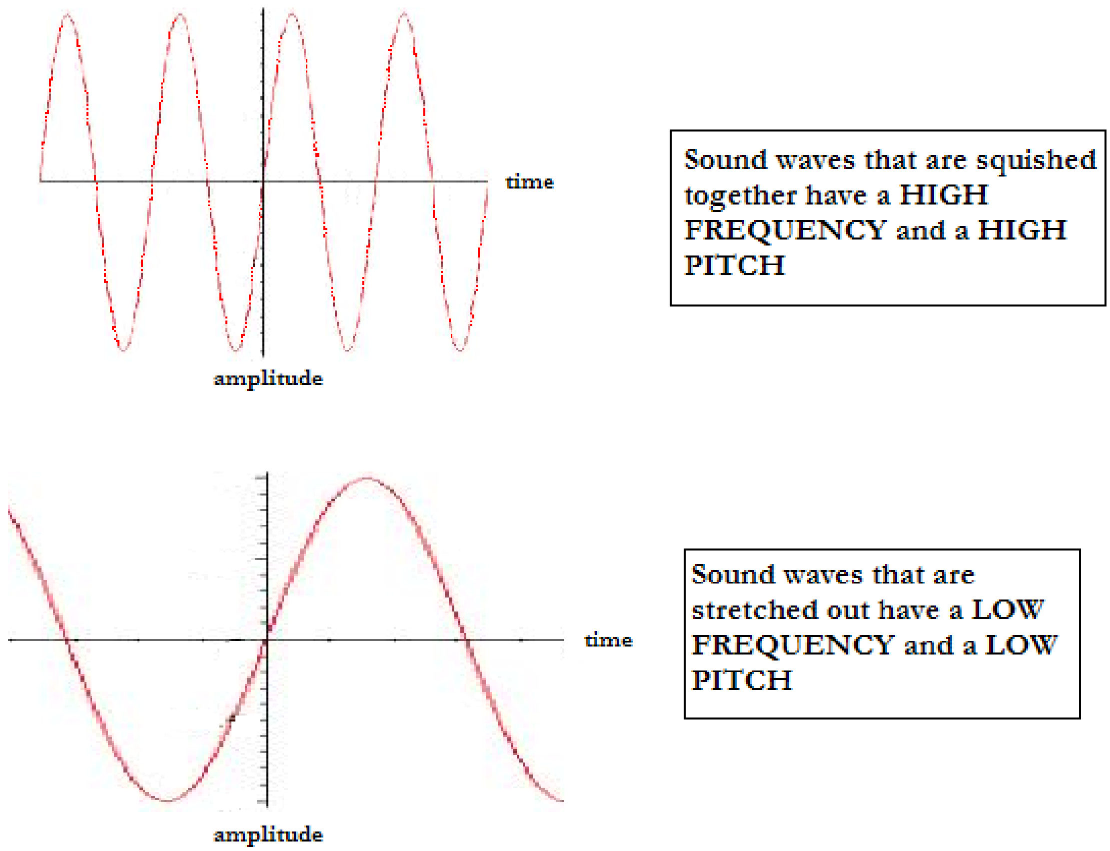
Sound, as you may know, has wave-like properties when it travels through air. Just like the waves that roll up onto the beach, sound waves have crests and valleys. How tall and how deep those crests and valleys are will determine the **amplitude** and loudness of the sound. Sound waves that are very tall and deep will be very loud, and sound waves that are short and shallow will be very quiet (Figure 1).

Figure 1 - Low amplitude (quiet) sound waves compared to high amplitude (loud) sound waves



The distance between the crests and valleys will determine the **frequency**, or what is commonly known as the pitch of the sound. If the waves are squished together, the sound will be very high pitched and squeaky and if the waves are stretched out, the sound will be low pitched, like a low hum (Figure 2).

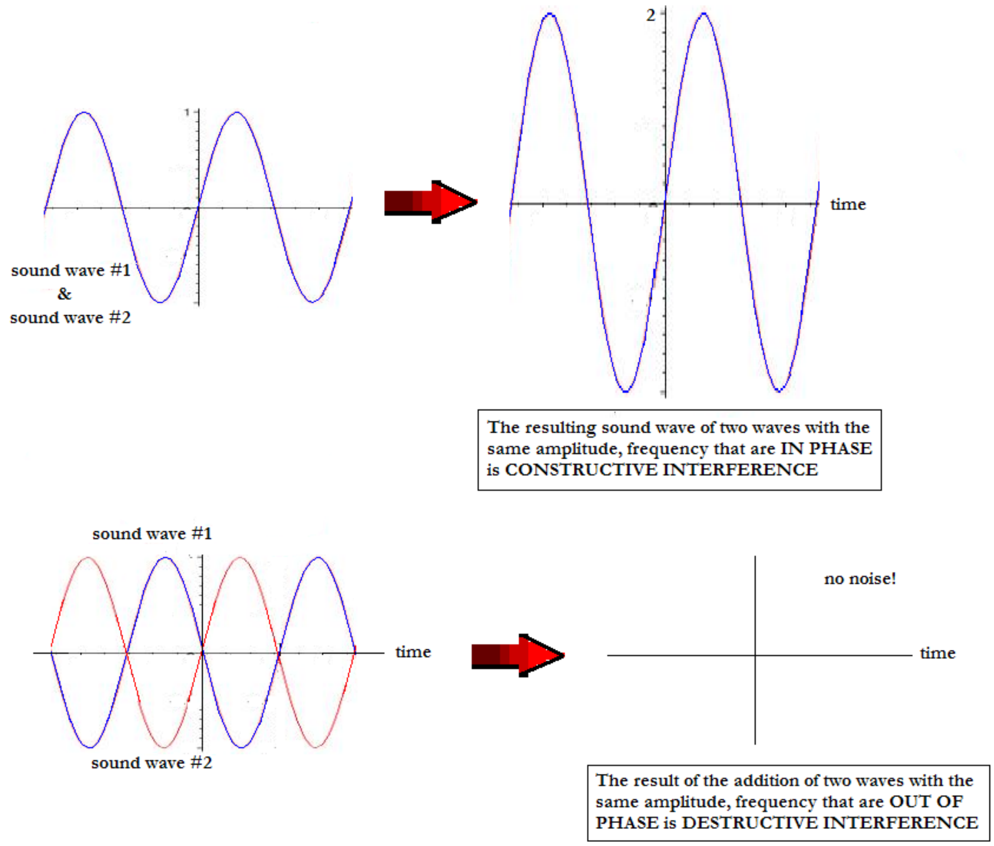
Figure 2 - High frequency/pitch sound waves compared to low frequency/pitch sound waves



If there are two sound waves present, the waves overlap and "interfere" with each other. When the two waves have the same frequency and directly overlap (i.e. they have the same phase) the result is **constructive interference** and the noise will double in amplitude. However, if the two waves have the same frequency and amplitude but they are shifted slightly in time (i.e. they are "out of phase"), then the waves cancel each other out and you get **destructive interference**. The result of destructive interference is that no noise (or sound) will be heard (Figure 3).

Active noise control uses destructive interference to cancel out unwanted noise. The frequency, amplitude and phase of the undesired sound are measured and another sound of the same frequency and amplitude but opposite phase is created. When destructive interference occurs, noise is reduced. Therefore, in order for active noise control to function, it is necessary to know the frequency, amplitude and phase of the undesired sound. Active noise control works best for cancelling lower frequency sounds that are continuous; higher frequency and impulse sounds are hard to control.

Figure 3 - Constructive interference compared to destructive interference



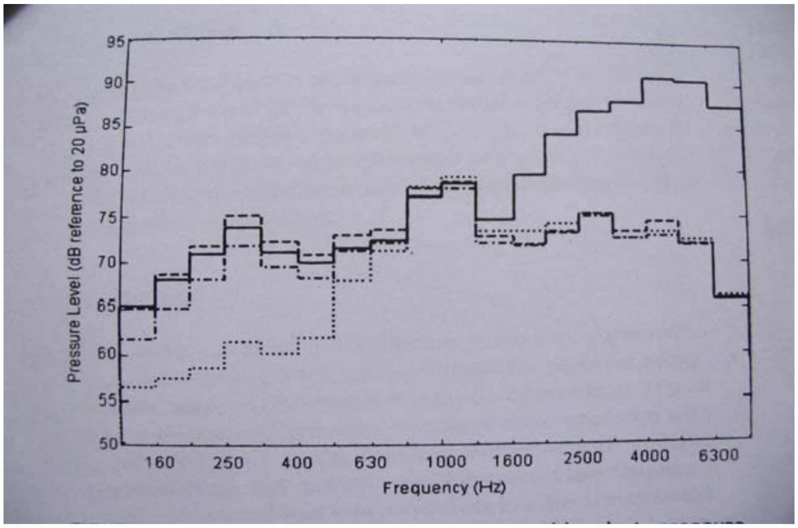
Active noise control headsets

Active noise control headsets are very similar to regular communication headsets (i.e. one or two-way communication) except that they have built in active noise control systems that reduce the amount of lower frequency **ambient noise** (i.e. the noise created by surroundings) so that the wearer will be able to better hear the higher frequency sound and speech that is being transmitted to the headset. These headsets are available commercially and are produced by several companies for a variety of industries. They also come in a variety of styles, from those that only cover part of the ear, to those that surround the entire ear, like an ear muff hearing protector. (Behar 2001) The latter type of headset is more useful because they can reduce the noise produced by sounds across a spectrum of frequencies (a.k.a. **broadband noise**). With the active noise control turned off, the headset functions similarly to an ear muff hearing protector, which decreases the sound in the high frequency range (high pitched sounds). This can be seen in Figure 4 taken from Feist, Mongeau et al. 2001. It shows three sound traces:

- The uncontrolled sound (solid line)
- The sound experienced while wearing the ANC headset, but with the ANC function turned off (dashed line)
- The sound experienced while wearing the ANC headset, but with the ANC function turned on (dotted line)

Sound is on the vertical axis and frequency is located on the horizontal axis.

Figure 4 - Effect of ANC headset on sound levels



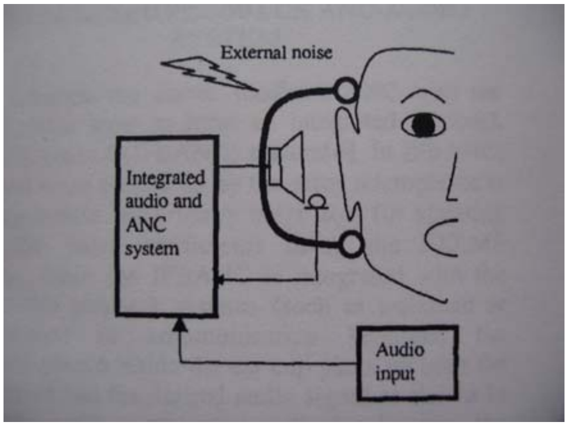
So how does the active noise control system know the all important characteristics of the noise it is trying to reduce such as the frequency, amplitude and phase as discussed in the previous section? Well, there are essentially two types of active noise control (ANC) that are currently being researched, each with their own advantages and disadvantages. These two types are "feed-forward ANC" and "feed-back ANC". (University of Twente 2005)

In **feed-forward ANC**, the system is programmed to cancel out a specific noise. That is, the frequency and amplitude of the sound are known, and they can be programmed into the system and a secondary noise is created which cancels out the first noise. (Pawelczyk 2003) This type of ANC is most useful when the noise exposure is continuous and predictable. An example of such noise may be the noise created by the vibration of a tractor. (University of Twente 2005) Headsets of this type are not appropriate if the unwanted external noise is being created by a moving source as the amplitude of the noise will not consistent in this circumstance – it will vary as the distance between the source and the receiver changes. (Gan and Kuo 2002)

In **feed-back ANC**, a small microphone located on the earshell of the headset picks up the signal of the external noise. This signal from the primary noise is analyzed for its frequency, amplitude and phase, and a secondary noise is created by the system that will result in destructive interference and cancel out the noise. This type of ANC is most useful when the noise you are attempting to reduce is broadband or unpredictable in terms of frequency or amplitude. It is a more accurate noise cancellation method than feed-forward ANC. You can have different signals being received and processed at each ear. (Gan and Kuo 2002) It is also considered to be cheaper and more compact than feed-forward ANC. (Gan and Kuo 2002) Figure 5 was taken from Gan and Kuo 2002 and shows the basic setup of a feed-back ANC system.

However, it may be possible to get the best of both worlds. Researchers are currently looking at **combining the two systems** (feed-forward and feed-back) in a single headset. The feed-back control is thought to reduce broadband noise while the feed-forward system reduces periodic noise. (Rafaely and Jones 2002) It may also be possible to get ANC headsets that control the noise that is transmitted to the ear from vibration of the earshell using vibration actuators which produce a force that opposes the **earshell vibration**. (Rafaely, Carrilho et al. 2002)

Figure 5 - Basic setup of a feed-back ANC headset



How might active noise control communication headsets be useful in the entertainment industry?

Now who might benefit from ANC communication headsets? To date, they have been used primarily by airplane pilots to reduce low frequency aircraft noise (Gower and Casali 1994; Giguere, Abel et al. 2000). They have also been tested by tollbooth operators for their ability to reduce traffic noise (Feist, Mongeau et al. 2001). Table 2 in the Appendix provides more detail on the studies that have been conducted assessing noise exposure from headsets. However, it seems completely plausible that ANC communication headsets, particularly those that are regulated by feed-back mechanisms, would be of use in the entertainment industry. They may be able to reduce the ambient noise on movie sets for example, thus increasing the wearer's ability to hear and understand the conversation being communicated through the headset itself, often referred to as speech intelligibility.

Although no studies have been conducted to date on the noise exposure from communication headsets in the entertainment industry, it is suspected that noise exposure may take one of two forms. Either the unwanted noise is loud ambient noise that is interfering with speech intelligibility or the unwanted noise is created by the headset itself (e.g. from feed-back or static). In order to determine if active noise control will be useful in your particular work situation, you will need to understand the nature of the source of the noise, and whether its frequency is low or high.

Is your unwanted noise external background noise?

In the first case where the unwanted noise is external **background noise**, the problem can be solved using active noise control. In such instances, it will be necessary to conduct a noise survey to assess your exposure to noise. In particular you will want to know the frequency range and the loudness of your noise source or sources, and whether or not the sound varies for any reason – for example is it stationary relative to your position.

Are the frequency and amplitude variable? Is the distance between you and the noise source changing?

If you find that the noise has varying frequency and amplitude, or that you or the noise source move around a lot, then feed-back ANC headsets will likely be more useful. It is expected that most of the situations that you will encounter in the entertainment industry will fall in this category (e.g. loud explosions or people talking around you). As can be seen from Table 1 below, there are many feed-back ANC headsets available commercially. Of these, the David Clark website is the easiest to navigate, and their headsets come in a variety of styles for a number of different uses. However, some of these manufacturers only produce ANC headsets for the airline industry. It may also be possible to modify an existing headset by fitting a microphone inside the earshell connected to an analog feedback control circuit. The Lectret headset was modified in this manner. (Rafaely and Jones 2002)

Are the frequency and amplitude of the noise constant? Is the distance between you and the noise source consistent?

If you find that the noise is relatively constant in frequency, loudness and distance, then a feed-forward ANC headset may provide adequate protection. Most situations in the entertainment industry will not fall under this category. However, if you find that you are exposed to this kind of noise, feed-forward headsets are also available commercially, possibly by some of the same manufacturers that are listed in Table 1.

If you would like to read about further studies that have evaluated, tested or produced ANC communication headsets, then refer to Table 3 in the Appendix. (Note: This table has a high level of detail and is intended for those readers with a good understanding of noise and active noise control.)

Table 1 - ANC headsets that have been identified in the scientific literature and reference websites where more information (e.g. prices) may be obtained

Headset	Description and performance	Reference	Website
ANVT	Supra-aural headset with ANC at 70-400 Hz, and passive noise control above 3000 Hz	(Zera, Brammer et al. 1997)	n/a
Bose Aviation headset	circumaural headset designed for aviation industry, feedback ANC	(Gower and Casali 1994; Giguere, Abel et al. 2000)	http://qualitysound.bose.com/headsetx_headset_index.htm
David Clark H1013X/DCNC	unknown	(Giguere, Abel et al. 2000)	http://www.davidclark.com/
QuietMan headset by MNC	circumaural headset with attenuation of frequencies below 1000 Hz	(Zera, Brammer et al. 1997)	n/a
Noise Control Technology Group	Feed-back	(Feist, Mongeau et al. 2001)	http://www.nctgroupinc.com/nbex.htm
Peltor 7004	circumaural headset, attenuates frequencies below 300 Hz	(Zera, Brammer et al. 1997)	discontinued product
Peltor ANR Aviation headset	active personal hearing protection device	(Giguere, Abel et al. 2000)	
Sennheiser NoiseGard	Feed-back	(Giguere, Abel et al. 2000)	http://www.pilotstuff.com/Sennheiser.html
TechnoFirst NoiseMaster	unknown	(Giguere, Abel et al. 2000)	http://www.volez.com/store/article.tpl?ref=TECHFIRST_CASQUE1 (in French)
Telex ANR 4000	Feed-back	(Giguere, Abel et al. 2000)	n/a

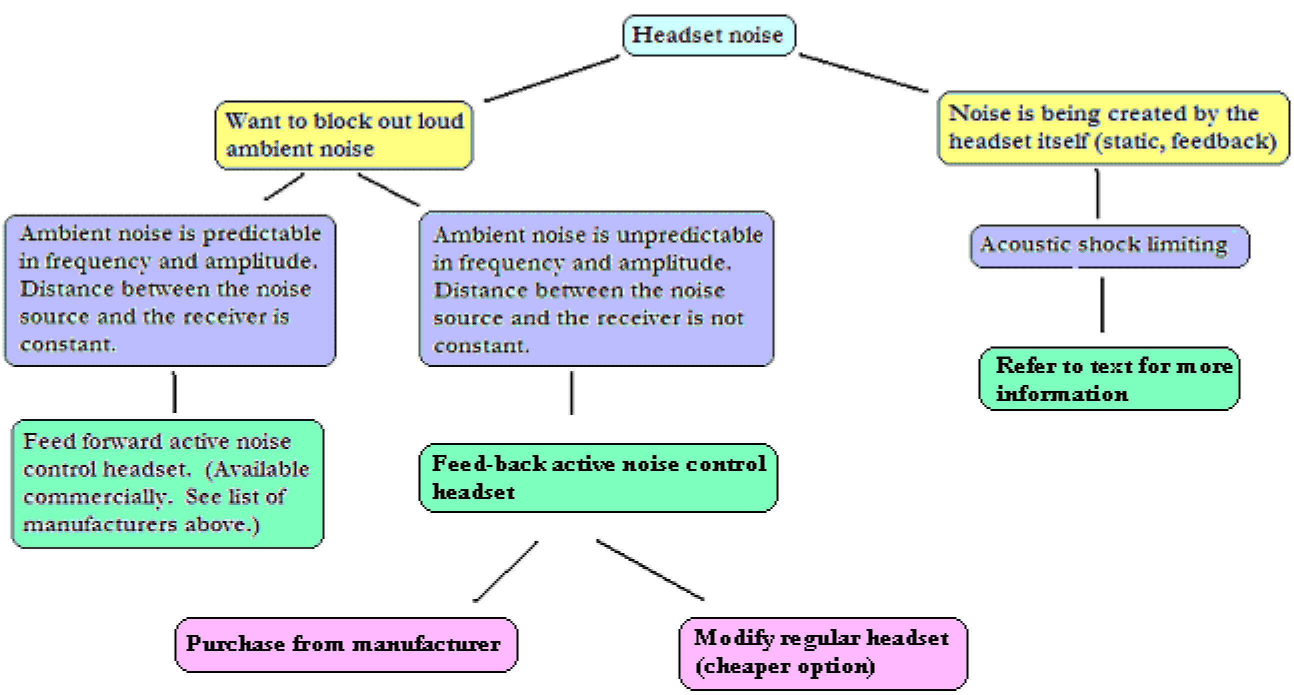
Is your unwanted noise emitted by the headset?

If the unwanted noise is more akin to the second case where the **noise is being emitted by the headset** itself, then active noise control may not be as useful. Several noise exposure studies have been conducted on call centre operators and telephone operators who may be exposed to noise from fax machines or acoustic feedback through their headsets. (Macrae 1995; Brueck 2003; Peretti, Pedrielli et al. 2003; Bayley 2004) In one particular study, the noise exposures of 150 call centre operators were measured. (Patel and Broughton 2002) Although the authors concluded that the call centre operators had a low risk of hearing damage from their occupational noise exposure they did suggest that the instalment of **acoustic shock limiters** may reduce their noise exposures. Acoustic shock limiters control noise in the form of short sound bursts. Discussions of this method of noise control go beyond the scope of this report, but the authors refer to the work of a group of scientists in Australia that may provide more information and that are studying the adverse health effects of these acoustic shock events. (Milhinch and Doyle 2000; Patuzzi, Milhinch et al. 2000)

Summary

The following is designed to assist in choosing the appropriate noise control strategy for your headset noise problem.

Figure 6 - Picking the appropriate noise control strategy



In conclusion, now that you know what active noise control is and how it works in ANC communication headsets, you should now be able to decide if an ANC communication headset will work for your particular headset noise exposure problem, and which one you should consider buying or modifying.

Acknowledgements

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Appendix 1: Literature Search Strategy

Four bibliographic databases were used to identify the literature for this review: PubMed, CCINFOWeb, Compendex/Inspec, and Web of Science. PubMed, produced by the U.S. National Library of Medicine, specializes in health literature. CCINFOWeb, produced by the Canadian Centre for Occupational Health and Safety, specializes in occupational health and safety literature. Compendex contains information on engineering, and some noise measurement papers were located using this database. The search was conducted in February 2005 and employed combinations of the following keywords: noise and exposure, headphones, headsets, earphones, cryptoling*, hearing protectors, active noise control. In addition, a significant portion of the literature cited within this review was identified through pearling, or hand searching of references found within other papers. We excluded articles which were written in languages other than English and French. Finally, with respect to potential control measures, a Patent search was conducted using similar search terms.

Appendix 2: Summary of articles that assessed noise exposure from headsets

Author & Date	Publication type	Purpose	Population	Method	Results	Comments
(Macrae 1995)	Primary	To determine an optimal method for measuring noise exposure at the eardrum to telephonists that use headphones or insert earphones while working	telephonists	Proposes two methods for measuring noise from the earphones at the eardrum, a probe-tube microphone inserted into the ear canal and a coupler		Identifies telephonists as an at risk group, and lists Australian OEL for noise exposure at the eardrum (8hr-LeqA = 90 dB, and Lpeak of 143 dB)
(Dajani, Kunov et al. 1996)	Primary	Measurement on noise exposure from communication headsets on an acousto-mechanical mannequin head. Method validation on human subjects in real-world applications	mannequin head, 8 industries: air traffic controllers, telephone operator, reservations operators, telephone cable maintenance workers and airport ground crew	For human measurements, measured noise levels under the headset (variety of types) with microphone and environmental noise was measured with a sound level meter	People that worked in the airport had higher Leq8hr than office or street setting. High environmental noise may contribute to noise exposure becasue it causes workers to increase levels so that they can hear. Greater attenuation with modified circumaural hearing protector	Looked at noise exposure from the headset itself and from the environment

Author & Date	Publication type	Purpose	Population	Method	Results	Comments
(Williams and Presbury 2003)	Primary	noise exposure from headphones that allow monitoring of broadcast transmission and receive information from program producers	radio announcers (12)	During broadcast, an identical headphone was set up in parallel on an artificial ear connected to a sound level meter	Most not exposed to high noise exposures but some do have high noise exposures (Leq up to 95 dB)	Radio announcers may be a special case because they are using headphones to monitor their own quality of voice transmission
(Patel and Broughton 2002)	Primary	To measure noise exposure of call centre operators	Call centre operators (150)	An identical headphone was set up in parallel on a KEMAR mannequin connected to a microphone at the eardrum. Only measured in left ear. Right ear was sealed. Background noise levels were measured but not incorporated into estimate of Leq because not considered to be significant contribution	Noise exposure unlikely to exceed 85dBA, risk of hearing damage is low. Higher exposures from fax tones, holding tones and high pitched tones from mobile phones (but shorter in duration so don't contribute much to overall exposure)	Large sample size. In discussion, mentions some control strategies: acoustic shock limiters (short sound bursts) (legal requirement DTI 85/013). Refers to work of Patuzzi (2000) and Milhinch and Doyle (2000) who are studying health effects of acoustic shock events.
(Ritter and Perkins 2001)	Primary	To assess noise induced hearing loss in US air force cryptolinguists	Crypto-linguists (120)	Compared 1998 audiogram to reference audiogram and to enlistment audiogram.	Since incidence of PTS may exceed 3%, may signal that HCP is ineffective	Did not measure noise exposure itself.

Author & Date	Publication type	Purpose	Population	Method	Results	Comments
(Brueck 2003)	Conference summary (Measurement and instrumentation group)	review of presenters at the conference	call centre operators			
(Peretti, Pedrielli et al. 2003)	Primary	headphone noise exposure	telephone operator	head and torso simulator in 3 different workplace settings	Some workers may be at risk for hearing loss	
(Savell and Boothby 1996)	conference proceedings	to assess the noise exposure of workers given personal (music) radio headsets, especially worried about workers that raise the volume of their headsets in order to hear over background noise levels	two groups control and treatment (i.e. headset with adjustable volume)	Headsets were of two types: walkman with headphones and headsets with radio incorporated into the headset, and were measured on artificial test fixture	May result in overexposure (based on OSHA criterion of 80 dB), if headphones are turned up to highest volume for the entire 8 hour workday (range of 90 to 99 dBA TWA)	Authors did not expect the headphones to attenuate any of the background noise (not even passively). In fact, specifically avoided earmuff type headsets because they attenuate the noise.

Appendix 3: Summary of ANC headset articles

Author	Publication type	Control type	Product(s)	Theory/Purpose	Methods	Results	Comments
(Bayley 2004) (representative from Plantronics)	Review	Telephone headsets, acoustic limiting	Mention Plantronics as a manufacturer for these devices	Noise spikes may occur in cordless telephones (analogue, digital or Voice-over-IP), longer duration noises from fax or DTMF tones, acoustic feedback or network faults.		Acoustic limiting in cordless and mobile phones puts a limit on the voltage that can be transmitted through the telephone headset.	This technology is more useful if the noise is being emitted from the headset itself rather than exterior to the headset (ambient noise). Also could this technology be adaptable from telephones to sound attenuating headsets?
(Behar 2001)	Primary	ANR headsets	one supra-aural headset, 2 circumaural headsets, one flying helmet (No brands/models specified)	To compare insertion loss that is achieved from the different headset designs	Acoustical test fixture (artificial head) which allows for measurement of insertion loss. Pink noise emitted by loudspeakers in audiometric cabin	circumaural headsets seem to provide greater total insertion loss (approximately 15 dB below 500 Hz) than supra-aural (4 dB below 500 Hz)	
(Brammer, Peterson et al. 2004)	Primary	ANR headsets	one feedback control headset and one feedforward control headset (brands/model not specified)	Comparison of the ability of the two headsets to maintain speech intelligibility	Headsets are worn by human or mannequin and noise reduction is measured using microphone inserted under earmuff. Speech transmission index (STI) was used to determine speech intelligibility.	In feedback control system, when input mic is located under the earmuff there is cancellation of noise and speech. Not a problem with feedforward.	

Author	**Publication type**	**Control type**	**Product(s)**	**Theory/Purpose**	**Methods**	**Results**	**Comments**
(Campbell 1975)	Review	noise-attenuating headset	n/a	n/a	n/a	n/a	Describes how to measure effectiveness of noise-attenuating headsets: acoustic attenuation, receiving sensitivity and frequency response of the headset, and microphone sensitivity
(Cartes, Ray et al. 2002) J Acoust Soc Am	Primary	ANR headset	modified prototype (Rockford Fosgate model FNQ1406)	Comparison of algorithms to optimize stability and performance of ANR systems	Headset is mounted with the earpieces on a flat plate in a low freq acoustic test cell and subjected to 4 noise sources.	They were able to pick a candidate algorithm which resulted in overall stability and performance in measured and simulated ANR experiments.	How accurate are flat plate measurements (our faces are not flat!)? Not sure what the implications are since this is a theoretical evaluation more than an evaluation of the headset itself.
(Cartes, Ray et al. 2002) Can Acoust	Primary	low frequency acoustic test cell		Describes the development of a low frequency acoustic test cell which can be used to evaluation circumaural ANR headsets			
(Cui, Behar et al. 2003)	Primary	ANR headsets	5 types of headsets (brands/models not specified)	Measurement of insertion loss of ANR headsets using experimenter designed acoustic test fixture (mannequin)			This is a proposed method for the measurement of insertion loss that doesn't involve human subjects.

Author	**Publication type**	**Control type**	**Product(s)**	**Theory/Purpose**	**Methods**	**Results**	**Comments**
(Feist, Mongeau et al. 2001)	Primary	active noise reduction headset	Noise Buster Extreme open ear active noise control headphone, manufactured by Noise Control Technology Group Inc.	To reduce low frequency ambient traffic noise levels through active noise control will reduce risk of developing hearing loss, increase speech intelligibility between attendant and customer and increase comfort level of attendant	Using two questionnaires, evaluated **subjective** response of tollbooth operators to ambient noise (eg. traffic) with and without open ear active noise control headphone.	Reduction in ambient noise but no increase in speech intelligibility. ANR headset attenuates noise in the low freq range (<500 Hz). Headset itself (ANR off) attenuates noise in high freq range. Attendants did not find them to be comfortable and were unlikely to wear them while working.	Subjective response to headsets
(Gan and Kuo 2002)	Review	Integrated feedback active noise control headsets	n/a	n/a	n/a	n/a	Easy to read, good background information. Explains advantages and disadvantages of feedforward and feedback control systems.
(Gan and Kuo 2003)	Primary	Integrated feedback active noise control headsets	designed by the authors	Describes the development and evaluation of an ANC headset	Integrated system that has feedback control combined with off-line and on-line modelling of the secondary path (i.e. noise picked up from error microphone), additional adaptive filter that cancels near-end noise before sending it to the far end. Had to develop algorithms to do this.	Based on computer simulation results, was able to attenuate the background noise by more than 30 dB while enhancing the near-end speech level by more than 25 dB	Disadvantage of combination analog feedback and digital feedforward is the limited flexibility of the analog filter. This system may be able to compensate for that.

Author	Publication type	Control type	Product(s)	Theory/Purpose	Methods	Results	Comments
(Gan and Kuo 2004)	Primary	ANR headset with good bass reproduction	not specified	ANR attenuates low frequency environmental noise, but may also reduce wanted bass (esp in headsets for portable MP3 players, etc)	Wubjective response to attenuation provided by headset when two sound tracks were played	Practical, cheap, lightweight and effective, cancels noise and enhances bass	
(Giguere, Abel et al. 2000)	Review	ANR headsets and binaural technology	Peltor ANR aviation headset, Sennheiser NoiseGard, Bose Aviation headset, Bose Aviation Series II, David Clark DCNC headset, David Clark H1013X, Telex ANR headset system, Telex ANR 4000, TechnoFirst NoiseMaster	Combination of ANR and binaural technology may allow for increase in speech intelligibility especially in aircraft cockpits	none presented	All headsets studied were analog, preferable to have digital because more compact. More research needed.	Binaural technology: signals are integrated from both ears

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(Gower and Casali 1994)	Primary	ANR and conventional headsets	ANC headset - Bose Aviation, conventional - David Clark H10-76	comparison of an ANR and conventional headset to see if the ANR increases speech intelligibility and noise attenuation in environments with high ambient noise (eg. aircraft noise)	Three headset configurations (ANR on, ANR off, and conventional) tested with pink (broadband) noise and M-2 Bradley Infantry vehicle (tank) (low freq bias esp at 50, 125, 250 Hz) noise emitted from loudspeakers in a lab on 9 subjects (6M, 3F) aged 19-26	Attenuation of noise with ANR headset, especially at low freq but no increase in speech intelligibility	This experiment was conducted in a laboratory environment, therefore the real-world application is questionable
(Pawelczyk 2002) Appl Acous	Primary	active noise reduction headset	passive headset (Peltor H9A) equipped with loudspeaker (headphone)	The authors modified a passive headset by equipping it with a loudspeaker to create an ANC headset, analog control	Noise attenuation was measured using a Solartron-Schlumberger spectral analyser	Attenuation of noise by 15-20 dB from 200-450 Hz. Analog control is best for short distances between noise source an error microphone. Cheap to produce (approx 20 USD including passive headset).	A highly technical review article.
(Pawelczyk 2002) J Sound Vib	Primary	feedforward active noise control in active personal hearing protection device	not commercially available, constructed by the author	construction of an algorithm that will allow for attenuation of sound in APHPD quickly	n/a	Attenuation of 30 dB over freq range 100 to 550 Hz, adaptation takes about 0.1 s.	Not sure if this device is commercially available yet…due to quick response, may be good for controlling periodic noise?

Author	Publication type	Control type	Product(s)	Theory/Purpose	Methods	Results	Comments
(Pawelczyk 2003)	Primary	ANR headset with hybrid feedback control	not commercially available, constructed by the author	Investigation of a hybrid (analogue and discrete) feedback control system. Analogue controller attenuates broadband noise, and discrete controller attenuates dominant tones		Perform as expected.	Excellent introduction on problems and issues surrounding ANR headsets.
(Rafaely and Jones 2002)	Primary	Feedback-feedforward ANR headset	modified Lectret ANR headset (circumaural with analog feedback control and digital feedforward control)	Feedback control reduces broadband noise while feedforward reduces periodic noise	One subject was fitted with headset and exposed to white noise that was passed through filters in range 200 to 900 Hz in reverberation chamber (reverberant sound field) and laboratory (direct sound field). Noise measured with internal microphone.	Good broadband sound attenuation in reverberant sound field regardless of subject position. In direct sound field, best attenuation is achieved when the external reference mic is upstream of the propagating sound field.	Requires modification of commercially available headset. Only one subject.
(Rafaely, Carrilho et al. 2002)	Primary	ANR headset with earshell vibration control	modified passive headset (JSP, model KMO7236)	Additional noise that is transmitted to the ear via earshell vibration is reduced using vibration actuators which produce a force that opposes the earshell vibration instead of generating sound inside of the earshell as is the theory behind conventional ANR headsets	Theoretical model was constructed to predict how changes to the headset (inertial force actuator or a force actuator) would cause a reduction in earshell vibration. Followed up by experimental validation.	The preferable configuration involves the placement of a force actuator between the headband and the earshell because it does not increase the inertial weight or compromise comfort.	Requires modification of commercially available headset. Theoretical and laboratory based…real-world function?

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(Zera, Brammer et al. 1997)	Primary	ANC headsets	Peltor headset (model 7004), Quietman headset by MNC, and NQ100 hearing protector by ANVT	comparison of subjective (masked threshold, loudness balance) and objective (insertion loss) measures of active hearing protector and communication headset attenuation	In an anechoic chamber, subject (n=7) was surrounded by 4 loudspeakers emitting broadband (25-20000 Hz) pink noise at a sound pressure level of 110 dB while wearing hearing protection device	All three methods of measurement yielded similar results for Peltor. Peltor headset: ANC works primarily below 500 Hz, max attenuation of 18 dB at 125 Hz, NQ100 hearing protector: max attenuation of 17 dB at 200 Hz, not very good at attenuation in the high frequency range (4000-8000 Hz), smallest attenuation of all devices, Quietman headset: ANC functions at frequencies below 1000 Hz, range in attenuation with different subjects and different measurement techniques	Article has nice description and photos of all headsets. Peltor: circumaural headset, large volume earcup, attenuates sound below 300 Hz. Quietman: circumaural headset, smaller volume earcup, lighter, attenuates sound below 1000 Hz. NQ100: supra-aural, lightweight, attenuates sound from 70-400 Hz (actively) and above 3000 Hz (passively)