AERO-TACTILE INTEGRATION IN SPEECH PERCEPTION:

ADULTS WITH HEARING IMPAIRMENT

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Abstract

Human speech perception can be influenced by speech-related air-flow stimuli delivered to the skin, known as aero-tactile stimulation. Following on from a series of experiments conducted in listeners with normal hearing, our aim was to investigate whether the simultaneous presentation of auditory and aero-tactile components of speech would improve speech perception in noise of adults with sensorineural hearing impairment, compared to presentation of the auditory component alone. Participants undertook an open-set sentence test, with and without airflow. The auditory component was mixed with speech-weighted noise, and was presented through headphones, while the aero-tactile component was reproduced as air-puffs delivered through a small pump. The signal-to-noise ratio (SNR) was adjusted using an adaptive procedure to find the SNRs where participants obtained 20% and 80% of the sentence correct, and this information was used to derive psychometric functions that could be compared between groups. We hypothesised that the presence of aero-tactile stimuli would lead to improved speech perception, with speech recognition thresholds occurring at lower SNRs. There was no statistically significant difference between any of the independent variables with and without aero-tactile stimuli, regardless of degree of HI. Future directions include improvements to the current system such as increased airflow, with refinements made based on further research into the skin response to different airflow patterns.

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List of Abbreviations

AC	Air conduction
BC	Bone conduction
HI	Hearing impairment
NH	Normal hearing
NZ	New Zealand
PTA	Pure tone average
SNHI	Sensorineural hearing impairment
SNR	Signal-to-noise ratio
UCSHC	University of Canterbury Speech and Hearing Clinic

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Chapter 1. Introduction

1.1 Hearing Impairment

1.1.1 Prevalence of hearing impairment

Hearing impairment affects approximately 360 million people worldwide (World Health Organization [WHO], 2015) and between 7.5-9% of people in New Zealand to an extent that it affects their daily life (Exeter, Wu, Lee, & Searchfield, 2015; Statistics New Zealand, 2014). It is the most common sensory impairment affecting the lives of New Zealand adults, with a higher prevalence among males than females, and increases in prevalence with age (Exeter, Wu, Lee, & Searchfield, 2015; Statistics New Zealand, 2014).

1.1.2 Consequences of hearing impairment

Hearing impairment differs between individuals and can affect them in different ways. This can depend on the nature of the hearing impairment, the degree of hearing impairment, the age of onset, how rapidly it progresses, and other individual characteristics of the person (Kaland & Salvatore, 2002). A common issue found by people with hearing impairment is difficulty with speech perception, even when speech is amplified (Ching, Dillon, & Byrne; 1998; Hogan & Turner, 1998; Hornsby, Johnson, & Picou, 2011; Turner & Cummings, 1999). Hearing impairment can negatively affect an individual's ability to effectively communicate, and the impact this has on daily life is highly significant. Those with hearing impairment have a reduced quality of life (QoL), and report increases in loneliness, isolation, dependence, depression, and frustration (Ciorba, Bianchini, Pelucchi, & Pastore, 2012).

1.1.3 Management of hearing impairment

There are a number of strategies for managing hearing impairment. One of the most common is the use of amplification (in the form of hearing aids), or other assistive listening devices. These are able to improve the wearer's ability to detect sounds, and are beneficial to people of mild to profound degrees of HI. The use of amplification is shown to improve the both the individual's, and their communication partners, quality of life (QoL) (Kochkin & Rogin, 2000; Mulrow et al., 1990). Current hearing aids deliver speech in the auditory modality, however, there are other information-carrying components to speech that are in non-auditory modalities.

1.2 Multimodal Speech Perception

1.2.1 Overview

Speech perception is often considered to be the means of detecting, processing, and comprehending the auditory components of verbal communication. Although the auditory components of speech are important in its perception, it is not due to solely audition. Speech perception has been shown to be multimodal, with the integration of multiple sensory modalities influencing how speech information is perceived.

Significant research has been undertaken in this area, with a particular focus on the interaction of auditory and visual modalities in speech perception. More recently, this focus has shifted to other sensory modalities involved in speech perception, namely auditory-tactile integration, and visual-tactile integration.

1.2.2 Auditory-visual integration

Primary research on multimodal integration in speech perception was focused on the interaction of auditory and visual modalities, with expansive research having been undertaken in this area. Simultaneous presentation of both the visual and auditory information of a speaker has been shown to result in improved speech perception performance over presentation of the auditory stimuli alone, even in difficult listening situations. A number of studies have shown that when speech is difficult to hear, that being able to see the speaker leads to improved performance (Macleod & Summerfield, 1990; Reisberg, 1978; Sanders &

Goodrich, 1971; Sumby & Pollack, 1954;). These studies show that visual information can improve speech perception when there is a degraded auditory signal. Visual cues have also been shown to improve speech perception when speech is clearly audible, but is accented or contains more complex language (Arnold & Hill, 2001; Reisberg, McLean, & Goldfield, 1987)

On the other hand, the presentation of mismatched auditory and visual information can disrupt auditory perception. McGurk and MacDonald (1976) showed that presentation of the auditory component of one consonant paired with the visual component of another will often result in the perception of a different consonant altogether. This is known as the McGurk effect, and occurs regardless of whether you are aware of it or not (Summerfield & McGrath, 1984).

1.2.3 Auditory-tactile integration

1.2.3.1 Early research

The tactile modality has also been shown to influence speech perception, through studies on auditory-tactile integration. Preliminary research in this area has provided support for auditory-tactile integration, finding similar results to those in auditory-visual research, including auditory-tactile McGurk-type effects (Fowler & Dekle, 1991). One recurring technique used in earlier auditory-tactile research is the Tadoma method (Alcorn, 1932). This requires specific placement of the hand on a speaker's face in order to detect movements and vibration that take place during speech. A limitation to these preliminary studies is that participants either had an understanding of the purpose of the task (Fowler & Dekle, 1991; Gick, Jóhannsdóttir, Gibraiel, & Mühlbauer, 2008) or were practised at forming associations between multimodal information (Bernstein, Demorest, Coulter, & O'Connell, 1991; Reed, Durlach, Braida & Schultz, 1989; Sparks, Kuhl, Edmonds, & Gray, 1978).

1.2.3.2 Use of aero-tactile stimuli

More recent research has revealed that auditory-tactile information is integrated by participants that are unaware of the presence of the tactile stimuli, nor trained to form auditory-tactile associations. Gick and Derrick (2009) presented auditory stimuli with and without simultaneous presentation of aero-tactile stimuli. The auditory stimuli in each block had the same place of articulation, but were either aspirated or unaspirated. The aero-tactile stimuli used were mechanically reproduced, inaudible air puffs which were intended to simulate those produced by aspirated speech sounds. These were presented at one of two locations; either the hand, or the neck. Presentation of the air puffs alongside the auditory stimuli significantly increased the likelihood of participants perceiving them as aspirated, compared to hearing the syllables alone. This showed that tactile information does have an effect on speech perception, in much the same way as visual information.

1.3 Factors in Multimodal Speech Perception

1.3.1Temporal relationship between multi-modal stimuli

For both auditory-visual and auditory-tactile integration, the timing between the presentation of the different modalities can affect whether they are perceptually integrated. Munhall, Gribble, Sacco, and Ward (1996) found that the McGurk effect is observed when auditory stimuli precede visual stimuli by no more than 60 ms, and follow visual stimuli by no more than 180 ms. Outside of this range there is a significant decrease in the integration. Using a similar method to the study performed by Gick and Derrick (2009), Gick, Ikegami, and Derrick (2010) found temporal integration of auditory and tactile information to occur over a similar range as auditory-visual integration. Auditory-tactile integration was found when the aero-tactile information preceded the auditory stimulus by 50 ms, to when it followed the auditory stimulus by 200 ms. In both studies, this is attributed to physical laws and the frequency of which this is experienced in the ‘real world’. Light travels faster than sound; therefore in everyday life people often see events before they hear them. Similarly, the sound produced in speech travels faster than movement of air that is produced. Therefore there is an increased likelihood of integration when visual information precedes auditory information, and when auditory information precedes aero-tactile information.

1.3.2 Spatial relationship of aero-tactile stimuli

Further research by Derrick and Gick (2013) investigated whether the location of stimulus presentation was important in auditory-tactile integration by testing at a more distal location. The methods used were similar to the previous study (Gick & Derrick, 2009), but with the air puffs being presented at the ankle as it was “maximally distant from the ears, both physically and within the somatosensory cortex” (Derrick & Gick, 2013). As in the previous study, simultaneous presentation of the auditory and tactile stimuli increased the likelihood of participants perceiving them as aspirated. These results show that tactile information influences auditory perception, even when presented at distal body locations that are not thought to be regularly exposed to synchronous auditory-tactile stimulation. However, it has been shown that auditory-tactile integration does not take place when the air puffs are replaced with taps on the neck from a metal rod (Gick & Derrick, 2009), which indicates that the tactile information must be perceived as relevant to the auditory speech signal.

1.4 Progression of aero-tactile stimulation in auditory-tactile research

Gick and Derrick (2009) showed that the presence of an aero-tactile stimulus concurrently with the auditory presentation of labial and alveolar consonants increased the likelihood of them being perceived as aspirated. More recent studies have investigated whether auditory-tactile integration successfully improves speech perception over a larger range of speech sounds. Goldenberg, Tiede, and Whalen (2015) used three continua of sounds ranging from aspirated to unaspirated, as opposed to voiced and voiceless stimuli used in previous studies. They found that simultaneous presentation of air puffs increase the likelihood of labial sounds (/pa/ to /ba/) being perceived as voiceless, replicating the findings of previous papers (Gick & Derrick, 2009). Simultaneous presentation of air puffs lead to a slight increase in the likelihood of velar sounds (/ka/ to /ga/) being perceived as voiceless; and had no effect on the perception of vowel quality (/hɛd/ to /hɪd/). These results were anticipated by the researchers, as there is negligible difference in aspiration between the different velar and vowel sounds. Derrick, O'Beirne, De Rybel, and Hay (2014) also replicated and expanded on previous findings. Again, they found that the presence of an aero-tactile stimulus significantly increased the accuracy of identifying voiceless stops between voiceless and voiced stops, and also voiceless fricatives between voiceless fricatives and voiced stops. There was an increase in accuracy of identifying voiced fricatives between voiced fricatives and voiced stops, however this was not significant. The presence of aero-tactile stimuli did not affect ability to differentiate voiced stops and voiced affricates, as participants were already close to maximally accurate. There was also no effect of aero-tactile stimulation on differentiating voiceless stops vs. voiceless affricates, and voiceless fricatives vs. voiceless affricates. This was attributed to the difference in air flow information being too small to detect. The results of these two studies show that aero-tactile information influences perception of a range of speech sounds.

In previous studies, the aero-tactile stimuli were mechanically reproduced by the researcher to simulate those produced by aspirated speech sounds. To enable practical application of aero-tactile integration into technology, the air flow information needs to be obtained from speech at the same time as the auditory information. The study by Derrick et al. (2014) achieved this, reproducing that air flow using a small pump, which was found to improve speech perception as mentioned above.

The next step was to progress from testing with isolated aspects of speech (i.e. syllables) to assessing the effect of aero-tactile stimulation on speech perception in situations that more closely resemble real life communication, such as words and sentences.

In the partner study to the current one (Derrick et al., 2016), participants with normal hearing undertook open set speech recognition in noise using a matrix sentence test, with and without presentation of aero-tactile stimuli. The participants were in three groups: perceivers whose native dialect match that of the stimuli (NZ English perceivers), perceivers for whom English was a second language (L2 English perceivers), and perceivers whose first language was English but whose native dialect was not NZ English (foreign-accented English perceivers). Following methods similar to those used in the current study (and described in Section 2.6), participants were presented matrix sentence stimuli in noise, with and without artificial air flow (puffs) delivered to their forehead. As shown in Figure 1 below, these puffs had no effect whatsoever on their speech perception.

Figure 1. Psychometric functions from Derrick et al. (2016) showing no visible effect of air flow on speech perception for three groups of normal-hearing listeners: NZ English perceivers (n=20 listeners), L2 English perceivers (n=20 listeners), and foreign-accented English perceivers (n=8 listeners).

These results were somewhat surprising given the previous results from these experiments. The test was sensitive enough to detect differences in the perception of speech in noise between the different listener groups. While no effect was found for listeners with normal-hearing, it remained to assess whether the presence or absence of aero-tactile stimuli would influence the perception of speech in noise for listeners with a sensorineural hearing impairment.

1.5 Application of aero-tactile technology in people with hearing impairment

This technology has a wide variety of potential applications, particularly in enhancing speech perception in difficult listening situations i.e. the presence of background noise, unfamiliar speakers, lack of context, or when receiving auditory information alone (such as using the telephone). In these situations, people often rely on other communication strategies such as using context to infer what has been said (Dubno, Ahlstrom, & Horwitz, 2000; Stinson & Tracy, 1983), or using visual information from the speaker (Erber, 1969; Sanders & Goodrich, 1971; Sumby & Pollack, 1954). These strategies can be difficult to employ in all situations. If the airflow information of the speaker is able to be extracted and then reproduced on the listener's skin, the supplementary aero-tactile information could lead to increased speech perception of words that were ambiguous.

Up to this point, all research on the integration of auditory and aero-tactile stimulation has been undertaken on participants with normal hearing. However, one cohort that often has difficulty in challenging listening situations is people with hearing impairment. Depending on the degree, type, and configuration of hearing impairment, hearing impaired people often have poorer speech perception than normal hearing people; even when speech is amplified (Ching, Dillon, & Byrne; 1998; Hogan & Turner, 1998; Hornsby, Johnson, & Picou, 2011; Turner & Cummings, 1999). This is particularly true of difficult listening situations, such as background noise (Pekkarinen, Salmivalli, & Suonpää, 1990). When people with HI are unable to differentiate between sounds or words due to their hearing impairment, the aero-tactile input may provide another cue.

Research has also shown that people with hearing impairments are able to compensate for their hearing impairment using other sensory modalities. This was shown in the visual domain in people with early-onset hearing impairment, whereby their reliance on visual information is thought to result in the heightened speech reading capability of the participants (Auer & Bernstein, 2007). If this is also true of the tactile modality, people with hearing impairment are equally likely, if not more likely, to incorporate tactile information into speech perception as the normal hearing participants in previous studies.

1.6 Research aims and hypothesis

Gick and Derrick (2009), Derrick and Gick (2013), Derrick et al. (2014), and Goldenberg et al. (2015) all found that, in normal hearing participants, accuracy with perception of non-sentence auditory speech stimuli was improved when presented concurrently with aero-tactile stimuli. A study in listeners with normal hearing which overlapped with this one (Derrick et al., 2016), found no effect of airflow on the accuracy of speech perception using matrix sentences in noise. However, for the reasons described above, we hypothesised that there may be an effect found with people with hearing impairment - this would result in speech perception thresholds (20% correct and 80% correct) being at a lower SNR when sentences were paired with the aero-tactile stimuli.

With previous research being solely on participants with normal hearing, this research looked to provide evidence for how aero-tactile integration affects speech perception of people with hearing impairment. If concurrent auditory-tactile stimulation led to similar improvements in the speech perception of people with hearing impairment as people with normal hearing, this technology could begin to be incorporated into a number of assistive devices, such as hearing aids and telephones.

We hypothesised that the presentation of concurrent aero-tactile and auditory components of short sentences would result in improved speech perception of participants with hearing impairment, compared to presentation of the auditory component alone. This would be represented by speech reception thresholds being at a lower signal-to-noise ratio. However, it was unknown whether this effect would differ for differing degrees and configurations of hearing impairment, and whether the improvements would be greater at lower or higher SNRs.

Chapter 2. Method

2.1 Ethics

This study was approved by the University of Canterbury Human Ethics committee prior to this research commencing (latest amendment – Appendix A).

2.2 Participants

2.2.1 Inclusion/exclusion criteria

To be eligible to participate, participants had to be a minimum of 18 years of age, a fluent NZ English speaker, and have a hearing impairment (as defined in Section 2.2.2 below).

2.2.2 Hearing impairment

We analysed hearing thresholds at octave frequencies from 0.5 to 4 kHz, as this provided an approximation of participants overall hearing thresholds.

Hearing thresholds of less than or equal to 15dB HL are considered 'normal hearing' under the Goodman scale, which is used for the classification of degree of hearing impairment under UCSHC protocols and guidelines (University of Canterbury, 2016). Therefore, participants were required to have AC audiometric hearing thresholds at 20 dB HL or 'poorer' (i.e. greater than 20 dB HL) at no fewer than 3 out of the 4 octave frequencies between 0.5 and 4 kHz (i.e. 1 frequency could be 'better' than 20 dB).

We required participants' hearing impairment to be predominantly sensorineural. This was due to people with sensorineural hearing impairments having poorer performing performance in speech-in-noise tests (Leek & Summers, 1996) than people with normal hearing or conductive hearing impairment. The difference between AC and BC thresholds was generally required to be less than 15 dB HL.

As the auditory stimuli were delivered binaurally, we required participants to have hearing impairment that was bilateral and symmetrical. Therefore individual frequencies, from 0.5- 4 kHz, were to differ by a maximum of 15 dB HL between ears. The PTA (of 0.5, 1, 2, and 4 kHz) was to differ by less than 10 dB HL between the ears.

2.3 Recruitment

2.3.1 Database search

We recruited the majority of participants from the physical files of clients at the UCSHC that had indicated in their clinic enrolment form that students were permitted to access their information, and that they were willing to be contacted regarding participation in research.

2.3.2 Recruitment information and expression of interest

Potential participants were posted an envelope containing an information sheet (Appendix B) outlining the study and what is required of them should they agree to participate, along with information on contacting the researchers. A prepaid return postage envelope addressed to the researcher (the author) at the University of Canterbury was also provided.

A flowchart illustrating the recruitment and testing process is shown in Figure 2 below.

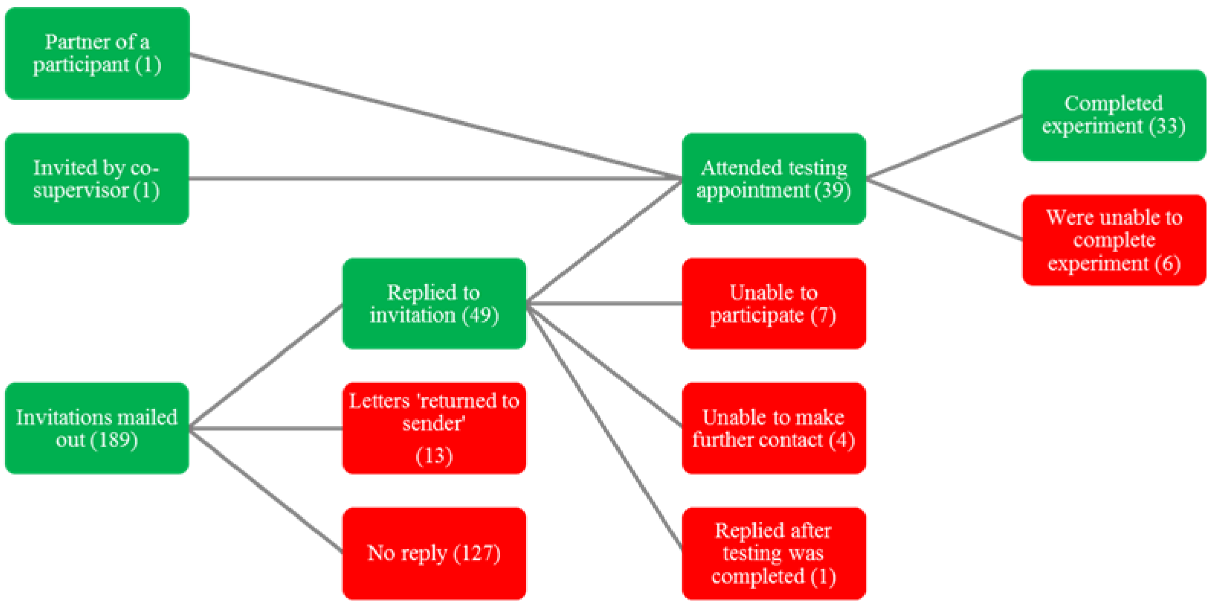

Figure 2. A flow chart illustrating the recruitment of participants into the experiment, and the withdrawal of invitees and participants from the process.

We posted invitations to participate in the study to 189 people from the UCSHC database that met the inclusion/exclusion criteria. Of these 189 invitees, 49 responded by either a) returning the letter of interest; b) leaving a message on the researcher's voicemail box; or c) emailing the researcher. The remainder of the invitations either elicited no reply (127) or were returned to sender (13) due to the invitees having moved house or died. The 49 who did respond were called back by the researcher and given a brief verbal summary of the study.

Of those 49, 37 were still willing and able to attend the testing appointment. A further two participants also joined the study at this point bringing the total to 39 participants. One was the partner of another participant invited to participate. They met the inclusion criteria and completed the experiment. The other was invited by the co-supervisor (DD), however was unable to complete the experiment, due to audiometric contraindications.

Of the 39 participants that attended the testing appointment, 33 were able to successfully complete all parts of the hearing test and experiment. Two were unable to participate in the experiment due to audiometric contraindications, and four completed the hearing tests, however decided to withdraw from the study due to loudness discomfort issues in the speech-in-noise test (see Discussion).

2.4 Pre-testing

Before participating in the experiment, participants received a verbal summary of the experiment, signed a formal consent form (Appendix C), and completed a Background Information Sheet (Appendix D).

2.4.1 The use of deception and misdirection

In accordance with our ethical approval, the information sheet we provided the participants stated that the aim of the experiment was to investigate how well people are able to identify different speech under conditions similar to those experienced by a pilot. We informed them that they would be listening to speech in noise through a special set of headphones, and may also experience airflow to the head during the speech. This misdirection was important in deterring participants from actively attending to the aero-tactile stimulation.

2.5 Hearing test

All testing took place within a single-walled audiometric booth (Industrial Acoustics Company Ltd., Hampshire, UK). We conducted a full hearing test on each participant according to UCSHC protocols and guidelines (University of Canterbury, 2016), including otoscopy (MacroView otoscope, Welch Allyn Ltd.), tympanometry (Madsen OTOflex 100 tympanometer, GN Otometrics Ltd.), and pure-tone audiometry from 250 – 8000 Hz via a calibrated Grason-

Stadler GSI 61 or a Interacoustics AD229e clinical audiometer (Interacoustics A/S, Assens, Denmark), using ER-3A insert earphones or Telephonics TDH-39 audiometric earphones for air-conduction stimuli, and a Radioear BC71 bone conductor for bone-conduction stimuli. If any audiometric contraindications were encountered, participants were unable to progress to the aero-tactile component of the experiment.

2.6 Aero-tactile speech discrimination task

2.6.1 Audiovisual Matrix Sentence Test

We based this test on the University of Canterbury Audiovisual Matrix Sentence Test (Trounson, 2012; O’Beirne, Trounson, McClelland, Jamaluddin, & Maclagan, 2015). We generated the test stimuli from the matrix displayed in Table 1 below.

Table 1. The matrix sentence stimuli

Name	Verb	Number	Adjective	Object
Amy	bought	two	big	bikes
David	gives	three	cheap	books
Hannah	got	four	dark	coats
Kathy	has	six	good	hats
Oscar	kept	eight	green	mugs
Peter	likes	nine	large	ships
Rachel	sees	ten	new	shirts
Sophie	sold	twelve	old	shoes
Thomas	wants	some	red	spoons
William	wins	those	small	toys

In this application, a new recording of the test was made using two speakers of New Zealand English - one male and one female - who had both their speech and the resultant airflow recorded simultaneously. We used the recordings from the male speaker in these experiments. The recordings consisted of the 50 words that comprised the 5 x 10 matrix, which were recorded without co-articulation. Each sentence used the same sentence structure (of the form 'name verb number adjective noun'). Examples of the sentences formed using this 5x10 matrix include "Thomas bought six new ships", "Peter wins two dark bikes", and "David has nine cheap shoes".

2.6.2 Normalisation and list formation

In a previous study (Derrick et al., in preparation), the recordings of the 50 words comprising the matrix were first normalised using eight normal hearing participants to ensure that each word was equally difficult in noise (i.e. had the same SRT). The noise itself was speaker-specific, created by randomly superimposing the 50 word recordings 10,000 times within a ten second looped sound file using an automated process. Noise created using this method results in a noise spectrum that is virtually identical to the long-term spectrum of the speech tokens from that speaker (Smits, Kapteyn, & Houtgast, 2004).

Psychometric functions for each word were gathered at four SNRs, and the level of each word was adjusted so that the midpoints of their psychometric functions were identical. This information was used to create 30 sublists of 10 sentences. All fifty words were present within each sublist (guaranteeing the same mean slope for each sublist), and no sentence was repeated across the 300 sentences. In order to have the slopes in each sublist to be as homogeneous as possible, an iterative process was carried out which generated 100,000 sublists of 10 sentences that contained all fifty words, retained the 30 most homogeneous that did not repeat sentences, and discarded the rest. The mean slope for each sublist was

29.6%/dB, and the average standard deviation of slopes of sentences in each list was 15.1%/dB.

2.6.3 Stimulus delivery

In the “puff” condition, the Aerotak speech production system (Derrick, et al., 2014; Derrick & De Rybel, 2014) was used to apply air flow to the participants’ temples. Briefly, the system works as follows: At the time that the audio signals for the test were recorded, a measurement of the airflow from the speaker’s mouth was made using a ping pong ball mounted on a carbon fibre rod placed in front of their lips. The deflections of the ball-rod complex were then used to produce an electrical signal proportional to the airflow, which was then recorded alongside the audio signal in a single wave (.wav) file (i.e. with the audio recording stored on one channel and the airflow recording on the other). This airflow signal was used to control a Murata MZB1001T02 piezoelectric pump (Tokyo, Japan) that was mounted to Panasonic RP-HT265 headphones to present the aero-tactile stimuli at the same time as the audio stimuli were presented via the headphones. The pump has the following specifications: the 5-95% rise time takes 30 ms (Derrick, et al., 2015), with a maximum pressure of 1.5 kPa during loud speech, and a maximum flow rate of 800 mL/min, which corresponds to about a twelfth of that of actual speech.

2.6.4 Aero-tactile test procedure

Participants wore the headset with the pump positioned 5.5 centimetres from the right temple. We presented the stimuli using the University of Canterbury Adaptive Speech Test (UCAST) platform (O’Beirne et al., 2015). The software was also used to record the response from the participants, who, in open-set mode, simply repeated what they heard. Individual words were marked as correct or incorrect, and were scored by the researcher using the response buttons shown in Figure 3 below.

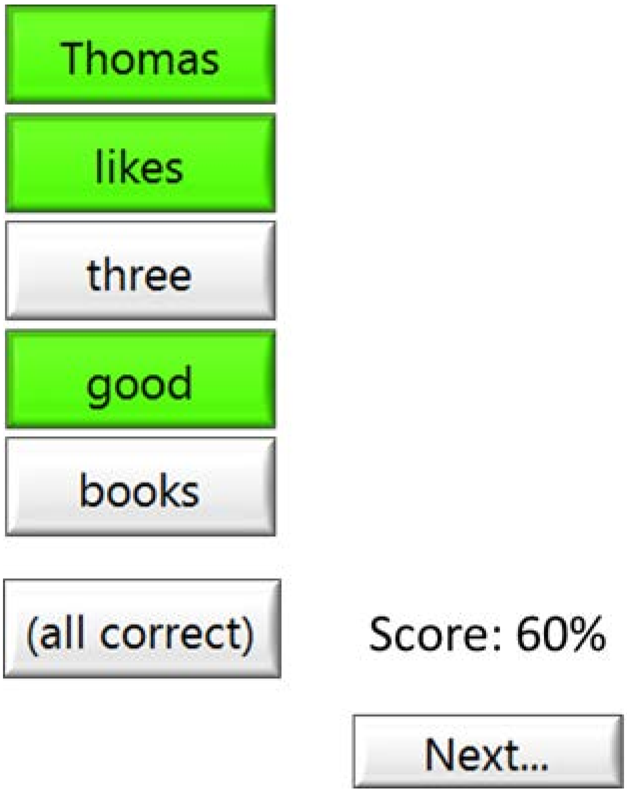

Figure 3. The graphical user interface used by the researcher to score the verbal responses from the participants. In this example, the sentence presented was "Thomas likes three good books", of which the participant correctly guessed "Thomas", "likes", and "good", resulting in a score of 60% for that sentence.

Two adaptive tracks were run in a randomly interleaved manner, following a modification of the A2 procedure of Brand & Kollmeier (2002). Starting at an SNR of -2 dB, each successive trial either increased or decreased the SNR depending on the proportion of correct words in the response. Examples of the two interleaved tracks are shown in Tables 2 and 3 below. Each adaptive track presented 15 sentences drawn from two concatenated and shuffled sublists (lists 6 and 14 in Table 2, and lists 16 and 23 in Table 3), and the entire test took just over five minutes.

Table 2. An example output for a 20% correct track.

Trial	SNR	Score	Time (s)	Actual	Chosen	Source
1	-2	60%	12.5	Hannah got three red spoons	Hannah ### three ### spoons	L14S02
2	-8	0%	31.6	William gives some cheap coats	### ### ### ### ###	L06S07
3	-5	20%	44.7	Kathy has those large hats	### has ### ### ###	L06S10
4	-4.75	0%	76.1	Kathy wins four new toys	### ### ### ### ###	L14S06
5	-3.24	40%	87.1	Oscar sees two green ships	Oscar sees ### ### ###	L14S05
6	-4.31	40%	99.8	Amy wants ten good hats	### wants ### ### hats	L14S08
7	-5.38	20%	128	Peter likes eight small books	Peter ### ### ### ###	L14S01
8	-5.13	0%	138.4	Sophie likes nine red books	### ### ### ### ###	L06S06
9	-4.37	80%	169.5	Hannah wants eight big shirts	Hannah wants eight big ###	L06S04
10	-5.99	20%	179.3	Thomas kept some cheap coats	### ### ### cheap ###	L14S10
11	-5.74	0%	214.5	Oscar kept four good shoes	### ### ### ### ###	L06S08
12	-5.36	20%	224.6	Peter sees two new bikes	Peter ### ### ### ###	L06S02
13	-5.11	20%	236.5	David sold ten small ships	David ### ### ### ###	L06S03
14	-4.86	0%	247.7	William sold nine old shirts	### ### ### ### ###	L14S07
15	-4.61	40%	258.4	Amy bought three dark mugs	### ### three dark ###	L06S09

Table 3. An example output for an 80% correct track.

Trial	SNR	Correct?	Time (s)	Actual	Chosen	Source
1	-2	80%	9.2	Hannah wins eight old hats	Hannah ### eight old hats	L23S08
2	-1.75	60%	24	William sold four small ships	William sold four ### ###	L23S07
3	1.25	60%	56.9	Sophie wants three dark toys	### wants three dark ###	L16S07
4	3.38	80%	67.7	Peter sees three large bikes	Peter sees three ### bikes	L23S09
5	3.63	100%	108.4	David likes some big spoons	David likes some big spoons	L23S06
6	2.56	100%	116.9	Amy bought six new mugs	Amy bought six new mugs	L16S05
7	1.49	80%	149.5	Kathy kept nine cheap mugs	Kathy ### nine cheap mugs	L23S01
8	1.74	80%	159.1	David kept four old ships	David kept four old ###	L16S03
9	1.99	100%	189.8	Rachel wants twelve good books	Rachel wants twelve good books	L23S02
10	1.45	100%	202.6	Thomas gives eight big books	Thomas gives eight big books	L16S04
11	0.91	40%	274.8	Kathy got nine green shoes	Kathy ### ### ### shoes	L16S01
12	1.99	100%	284.5	Oscar wins some cheap hats	Oscar wins some cheap hats	L16S08
13	1.61	80%	296.2	Amy bought six red shirts	Amy bought six red ###	L23S10
14	1.86	100%	305.4	Sophie has two dark shoes	Sophie has two dark shoes	L23S05
15	1.58	60%	316.7	Peter sees two good bikes	Peter sees two ### ###	L16S02

The two interleaved adaptive tracks work to place a large number of the trials in the region of the 20% and 80% portion of the psychometric curve (Brand & Kollmeier's so-called "pair of compromise"), which ensures that the fitted function is accurate in terms of both SRT and slope. The UCAST software used the Levenberg-Marquardt nonlinear regression algorithm to fit the function to the data points from both tracks, and gave as an output the SNRs at which the participant scored 20%, 50%, and 80% correct on this fitted function (the SNR20, SRT, and SNR80, respectively); and the slope of the fitted function at the SRT.

Participants were presented with 8 blocks, with each block alternating between the presence of the aero-tactile stimulus (Puff condition) or absence of the aero-tactile stimulus (No Puff condition). Whether the first presentation was the Puff or the No Puff conditions was alternated for each participant.

2.7 Debrief

At the conclusion of the testing appointment, participants completed a Debriefing Sheet (Appendix E) and were informed of the misdirection used in the experiment (See Section 2.4.1 above).

Chapter 3. Results

3.1 Results

We excluded data from analysis if:

i. The test was aborted for any reason
ii. The 20% or 80% level settled at or above 10 dB SNR – this was taken as a sign of attention lapse or lack of intelligibility due to distortion
iii. There were technical errors noted by the experimenter

This left 239 traces from 33 participants. We divided the data from the 33 participants somewhat arbitrarily into 3 groups of 11 based on their mean air-conduction pure-tone average (measured at 500 Hz, 1 kHz, 2 kHz, and 4 kHz). The pure-tone average characteristics of the three groups are shown in Table 4 below:

Table 4. Pure-tone average characteristics of the three hearing impaired groups. Note the non-overlapping ranges of the "Mean PTA" measure.

Pure-tone average characteristics	Hearing impaired Group 1		Hearing impaired Group 2		Hearing impaired Group 3	
	Mean ± SD (dB HL)	Range (dB HL)	Mean ± SD (dB HL)	Range (dB HL)	Mean ± SD (dB HL)	Range (dB HL)
Mean PTA	35.1 ± 2.7	29.4 to 38.1	41.6 ± 2.9	38.8 to 46.9	55.2 ± 5.2	47.5 to 64.4
Better ear PTA	33.3 ± 3.0	26.3 to 36.3	39.5 ± 3.0	35.0 to 45.0	53.4 ± 5.6	45.0 to 63.8
Worse ear PTA	36.9 ± 2.9	32.5 to 41.3	43.8 ± 3.4	38.8 to 50.0	57.0 ± 4.9	48.8 to 65.0

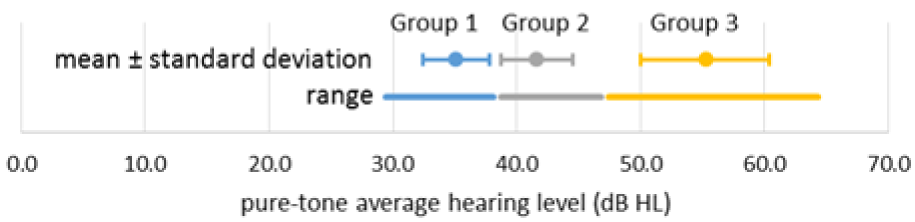

Figure 4. Graphical representation of the mean pure-tone averages of the three hearing impairment groups (n=11 participants per group).

Each participant performed an average of 3.6 tests in each of the puff and no-puff conditions. The stored output from each trial was the tracked SNRs at which the participant scored 20% and 80% correct, and the SRT and slope of the psychometric function fitted to the data (i.e. the SNR and proportion of words correct) from all 30 trials in each test. To obtain a better representation of the average SRT and slope for the each group (n = 11 participants) in the puff and no-puff conditions, we averaged the mean of the SNRs at which they scored 20% and 80%, and fitted a psychometric function to those two data points, the parameters of which are shown in Table 5 below as the "Fitted to mean 20/80" column.

Table 5. The mean data from hearing impaired groups 1, 2, and 3.

Hearing impaired Group 1		20%		80%		SRT		Slope		Fitted to mean 20/80	
	n	mean	± stdev	mean	± stdev	mean	± stdev	mean	± stdev	SRT	Slope
With puffs	42	-6.12	1.18	0.58	1.52	-2.77	1.09	11.97	4.84	-2.77	10.35
No puffs	41	-5.92	1.45	1.14	1.86	-2.39	1.49	10.81	2.72	-2.39	9.81

Hearing impaired Group 2		20%		80%		SRT		Slope		Fitted to mean 20/80	
	n	mean	± stdev	mean	± stdev	mean	± stdev	mean	± stdev	SRT	Slope
With puffs	38	-5.40	1.93	2.22	2.39	-1.60	2.06	10.07	1.97	-1.59	9.10
No puffs	37	-5.41	2.18	2.00	2.81	-1.71	2.45	15.13	19.22	-1.71	9.35

Hearing impaired Group 3		20%		80%		SRT		Slope		Fitted to mean 20/80	
	n	mean	± stdev	mean	± stdev	mean	± stdev	mean	± stdev	SRT	Slope
With puffs	41	-5.30	1.48	4.09	2.68	-0.60	1.78	9.26	3.69	-0.60	7.38
No puffs	40	-5.40	1.62	3.79	2.67	-0.81	1.96	8.27	2.29	-0.81	7.54

The psychometric functions plotted from the SRTs and slopes in the "fitted to mean 20/80" column are shown in Figure 5 below.

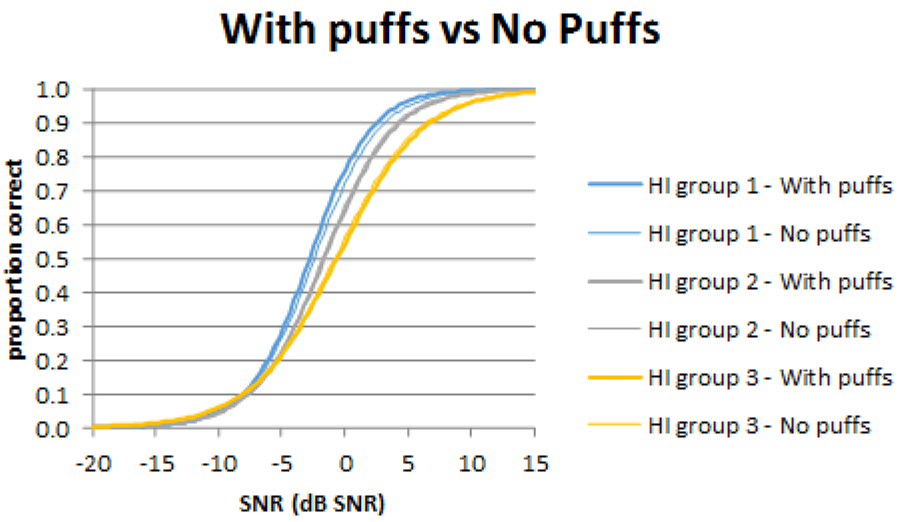

Figure 5. Psychometric functions for the three hearing impaired groups, with and without puff stimuli.

While clear differences are visible between the three groups, the differences between the “puff” and “no puff” traces within each group are barely discernible, particularly in groups 2 and 3 where the curves virtually overlie. Interpolating from the psychometric functions, the maximum differences between the puff and no puff curves are 4.2% at -1.2 dB SNR for Group 1, 1.4% at +0.8 dB SNR for Group 2, and 1.7% at +1.2 dB SNR for Group 3. Given that each five-word sentence was necessarily scored to the nearest 20%, these values are so small as to have no practical significance.

Interpolating from the psychometric functions in Figure 5, the maximum differences between the hearing impairment groups could also be determined. Without puffs, Group 1 scored a maximum of 7% better than Group 2 at -1.2 dB SNR, and a maximum of 16% better than Group 3 at +0.4 dB SNR. Group 2 scored a maximum of 10% better than Group 3 at +1.6 dB SNR. With puffs, Group 1 scored a maximum of 12% better than Group 2 at -0.8 dB SNR, and a maximum of 21% better than Group 3 at 0 dB SNR. Group 2 scored a maximum of 10% better than Group 3 at +1.6 dB SNR. This difference between Group 1 and Group 3 corresponded to approximately 1 extra word correct in each five word sentence near 0 dB SNR.

As there were only 11 participants in each of these groups, we did not conduct statistical tests on the group comparisons. Rather, we performed the following analyses on the data set as a whole.

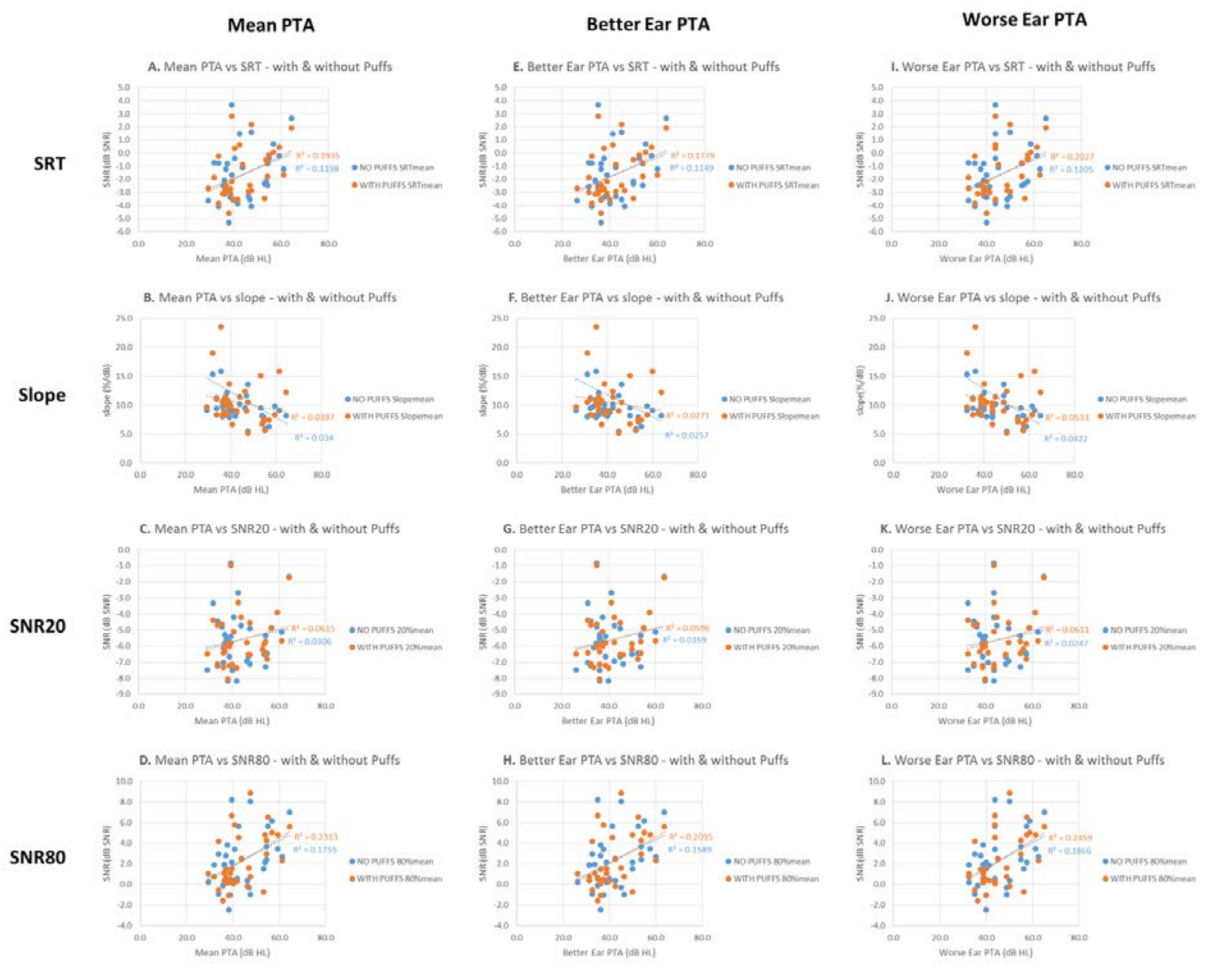

Figure 6. Correlations between pure-tone average [mean PTA (right column), better ear PTA (middle column), and worse ear PTA (left column)] and SRT, slope, SNR20, and SNR80 measures, with and without puff stimuli.

3.2 ANOVA

We performed a series of within-subjects repeated measures ANOVA to determine whether there were any significant effects of the puff stimulus on the following four measures:

- SNR20 – the signal-to-noise ratio at which the participant scored 20% correct
- SRT - the signal-to-noise ratio at which the participant scored 50% correct
- SNR80 – the signal-to-noise ratio at which the participant scored 80% correct
- Slope - the slope at the SRT of the psychometric function fitted to the SNR20 and SNR 80 data points.

The results of the ANOVA are shown below in Table 6. The ANOVA results show no statistically significant differences between any of these measures in the with and without puff conditions.

Table 6. Results of the one way ANOVA

	dF	F	sig.	partial eta squared
SNR20	1	0.007	0.936	0.000
SNR80	1	0.007	0.936	0.000
SRT	1	0.001	0.980	0.000
Slope	1	2.109	0.156	0.064
Error	31			

The only analysis that could potentially be of clinical significance was the difference in the slope. The partial eta squared in that analysis was .064, meaning that 6.4% of the variance in slope was accounted for by the air puff condition. A G*Power sample size analysis was performed, revealing that the study was underpowered and required 58 participants (with Power = .80 and Alpha = .05) to detect a significant effect of partial eta squared =.064. The 95% confidence interval for the difference between puff and no puff crossed the zero line for all dependent variables, indicating they are not significantly different, and their small size provides confidence in the result.

3.3 ANCOVA

In the event that the participants were relying on their better ear, we decided to also conduct a series of one-way analyses of covariance (ANCOVA), using better PTA (BEPTA) and worse ear PTA (WEPTA) as covariates in the analyses.

The results of these analyses are shown in Table 7. As with the ANOVA, there were no statistically significant differences between any of these measures in the with and without puff conditions, regardless of whether hearing impairment was controlled for. There was one significant interaction, though. The ANCOVA revealed a significant interaction between worse-ear PTA (WEPTA) and the SNR20 measure. This interaction is shown in the Panel K scatter plot in Figure 6.

Table 7. Result of the one way ANCOVA

	dF	F	sig.	partial eta squared
SNR20	1	1.682	0.205	0.055
SNR20*WEPTA	1	4.135	.051	.125
SNR20*BEPTA	1	4.806	.037	.142
SNR80	1	0.244	0.625	0.008
SRT	1	0.000	0.999	0.000
Slope	1	2.002	0.168	0.065
Error	29			

The effect size for the significant interaction between SNR20 and WEPTA is medium to large (Cohen, 1969), with 14.2% of the variance accounted for. The effect size for the non-significant ($p=0.051$) interaction between SNR20 and BEPTA was medium, with 12.5% of the variance accounted for. As in the ANOVA, the 95% confidence intervals for the difference between puff and no puff were small, and crossed the zero line, indicating they are not significantly different, and we can be confident in the result.

3.4 Comparisons between normal hearing and hearing impaired groups

In contrast to the current set of experiments, the data from the normal hearing participants was gathered using speech stimuli from both a male and a female speaker. In order to compare the normal hearing data with our own, which used only the male speaker, it was necessary to extract only the male-speaker data from normal hearing data set and reanalyse the results. Table 6 below presents the male-speaker data from the normal hearing participants and the current set of experiments together. The psychometric functions plotted from the SRTs and slopes in the "fitted to mean 20/80" column are shown in Figure 7 below.

Table 8. Male-speaker data from three normal hearing groups, and the three hearing impaired groups, with and without puff stimuli

Normal hearing NZ English perceivers - male speaker		20%		80%		SRT		Slope		Fitted to mean 20/80	
	n	mean	± stdev	mean	± stdev	mean	± stdev	mean	± stdev	SRT	Slope
With puffs	81	-8.19	1.11	-2.70	1.95	-5.45	1.41	14.01	4.27	-5.44	12.63
No puffs	79	-8.12	1.09	-2.74	2.07	-5.43	1.48	16.15	7.55	-5.43	12.88

Normal hearing L2 English perceivers - male speaker		20%		80%		SRT		Slope		Fitted to mean 20/80	
	n	mean	± stdev	mean	± stdev	mean	± stdev	mean	± stdev	SRT	Slope
With puffs	77	-7.64	1.28	0.43	2.87	-3.74	1.70	10.60	4.45	-3.60	8.59
No puffs	77	-7.70	1.53	0.00	3.14	-3.85	1.99	10.98	4.35	-3.85	9.00

Normal hearing foreign-accented English perceivers - male speaker		20%		80%		SRT		Slope		Fitted to mean 20/80	
	n	mean	± stdev	mean	± stdev	mean	± stdev	mean	± stdev	SRT	Slope
With puffs	21	-9.06	1.03	-2.92	2.14	-6.00	1.48	12.37	3.63	-5.99	11.29
No puffs	19	-8.84	0.56	-3.50	1.49	-6.17	0.93	14.24	4.02	-6.17	12.98

Hearing impaired Band 1		20%		80%		SRT		Slope		Fitted to mean 20/80	
	n	mean	± stdev	mean	± stdev	mean	± stdev	mean	± stdev	SRT	Slope
With puffs	42	-6.12	1.18	0.58	1.52	-2.77	1.09	11.97	4.84	-2.77	10.35
No puffs	41	-5.92	1.45	1.14	1.86	-2.39	1.49	10.81	2.72	-2.39	9.81

Hearing impaired Band 2		20%		80%		SRT		Slope		Fitted to mean 20/80	
	n	mean	± stdev	mean	± stdev	mean	± stdev	mean	± stdev	SRT	Slope
With puffs	38	-5.40	1.93	2.22	2.39	-1.60	2.06	10.07	1.97	-1.59	9.10
No puffs	37	-5.41	2.18	2.00	2.81	-1.71	2.45	15.13	19.22	-1.71	9.35

Hearing impaired Band 3		20%		80%		SRT		Slope		Fitted to mean 20/80	
	n	mean	± stdev	mean	± stdev	mean	± stdev	mean	± stdev	SRT	Slope
With puffs	41	-5.30	1.48	4.09	2.68	-0.60	1.78	9.26	3.69	-0.60	7.38
No puffs	40	-5.40	1.62	3.79	2.67	-0.81	1.96	8.27	2.29	-0.81	7.54

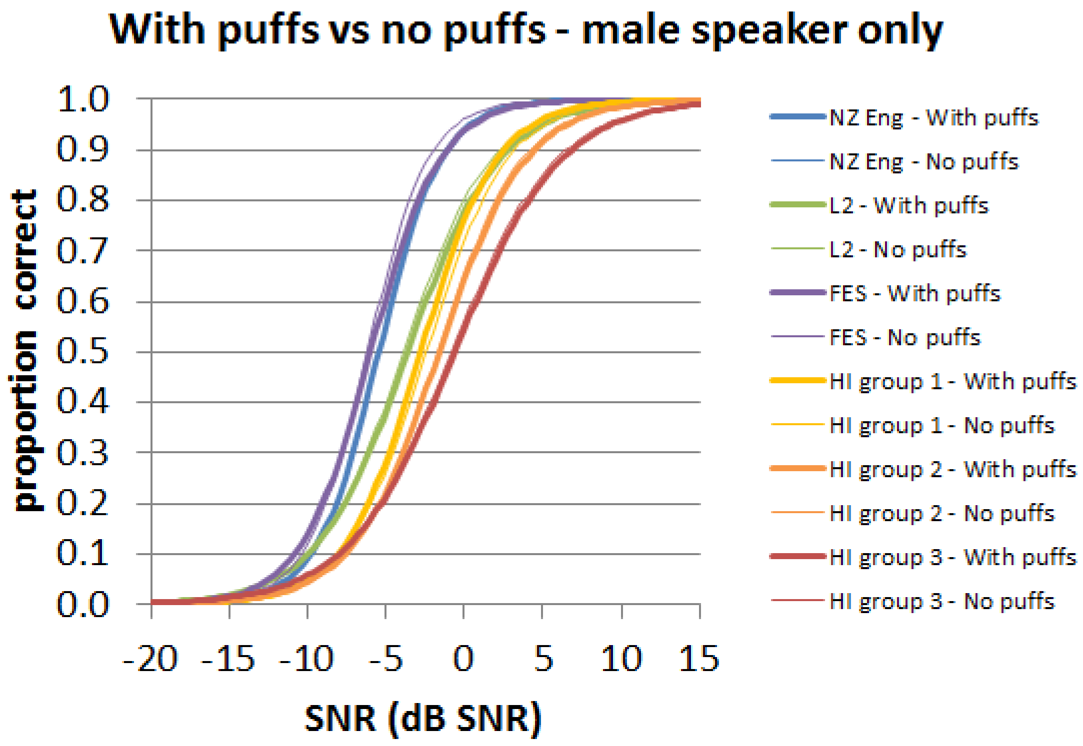

Figure 7. Psychometric functions for the three normal hearing groups, and the three hearing impaired groups, with and without puff stimuli.

Chapter 4. Discussion

4.1 Discussion

The results show that overall there was no statistically significant difference between any of the independent variables (SNR20, SNR80, SRT, Slope) in the puff and no-puff condition, regardless of whether or not degree of HI was controlled for. Therefore, these results did not support the hypothesis that the presentation of concurrent aero-tactile and auditory components of word stimuli in short sentences would result in improved speech perception of listeners with sensorineural hearing impairment, compared to the auditory component alone. While testing a greater number of participants would have given more statistical power, it wouldn't necessarily increase our confidence in the results.

The results were consistent with the results found in the partner study (Derrick et al., 2016) and shown in Figure 7 above, where the presence or absence of aero-tactile stimuli had no effect on the speech recognition in noise performance of participants with normal hearing undertaking a similar, open-set, matrix sentence test. Gick and Derrick (2009), Derrick and Gick (2013), Derrick et al. (2014), and Goldenberg et al. (2015) all found that, in participants with normal hearing, accuracy with perception of a wide range of isolated components of auditory speech stimuli was improved when presented concurrently with aero-tactile stimuli. One possible reason that this did not remain valid with speech in a sentence format is that the aero-tactile stimuli generated by the system were not strong enough to effectively mimic the air flow caused by speech. Although the stimuli were the same air pressure (1.5 kPa) as speech, they were only around 1/12th air flow (800 mL/s) of speech. This was due to the piezoelectric pump used in the Aerotak system having been designed to have low energy requirements to enable it to be applied to commercial devices, such as cellular phones. Therefore, a key improvement to the current system is a pump that produces airflow at a rate that more closely resembles the rate of air flow present in everyday speech. It was thought that positioning the output of the pump closer to the participants' skin would account for this. However, this potentially reduced the impact area of the air flow to the point where it did not effectively stimulate all four of the mechanoreceptors present in the skin. All four skin mechanoreceptors have been shown to respond to air flow present in speech (Mizobuchi et al., 2000). However, they have been shown to respond differently depending on the aero-tactile stimuli. Macefield (2005) found that one type of mechanoreceptor, Pacinian corpuscles, will respond to air that is blown on the skin through the lips, however will not respond to air blown on the skin through a straw. Consequently, in order to ensure that the airflow produced via the piezoelectric pump elicits a skin response that is homogeneous to speech, further research is required into how skin responds to a range of air flow presentation types.

Another explanation could be due to the participants' sense of touch. The majority of participants involved in the study were over 70 years of age. As with other sensory modalities, the sense of touch decreases with age. Thresholds for tactile stimuli are significantly increased in older adults, which is thought to be due to more sparsely distributed mechanoreceptors present in the skin, along with degeneration of the peripheral nervous system (Wickremaratchi & Llewelyn, 2006).

Another issue that needs to be resolved is the loudness discomfort experienced by some participants. A dual-track adaptive algorithm was used to adjust the SNR depending on the participants' performance in order to find the SNR where the participant was likely to get 80% of the sentence correct and 20% of the sentence correct. The adaptive algorithm (Brand & Kollmeier, 2002) assumes a maximum score of 100%, whereas in fact this is not achievable with some participants with SNHI due to the rollover. The end result is that there can be an increase in SNR to increasingly highly positive values, inducing loudness discomfort (and subsequent withdrawal of participants from the experiment) with no improvement in participant performance. At a high enough sound level, there may also be distortion of the sound within the system itself, affecting speech perception. Before further research takes place, the computer program needs to be adjusted to cap the maximum SNR.

A further limitation is participants becoming familiar with the words in the matrix after hearing words before in previous lists. This led to participants potentially being able to begin to guess words based on sentence structure (i.e. know that the second word is a verb). It also meant that participants could potentially have only heard part of the word, though were able to accurately guess what the word was. With only ten, fairly distinctive words recurring in each part of the sentence, there's a high likelihood of guessing the correct word once becoming more familiar with the experiment. Following on from this, it is easy for a participant to consistently get a word incorrect. The word 'ships' was often reported as 'chips', and recorded as an incorrect response. Depending on whether participants always reported 'ships', always reported 'chips', or alternated between the two could affect results. Interestingly, 'ch' and 'sh' are both high frequency sounds and could easily be misheard for each other by someone with SNHI. One possible solution to this could be to include more similar words in the matrix

Collating the results from both this and the partner study (Derrick et al., 2016), Figure 7 shows that there is a difference between the groups, with normal hearing perceivers whose native dialect match that of the stimuli (NZ English perceivers) and normal hearing perceivers whose first language was English but whose native dialect was not NZ English (foreign-accented English perceivers) getting a greater percentage of words correct at lower SNRs, followed by perceivers for whom English was a second language (L2 English perceivers), then followed by the three hearing impaired groups in order of increasing degree of hearing impairment. This indicates that i) the performance on the matrix sentence test was not affected by the accent of the native English listeners in these groups; and ii) the test was sensitive enough to detect differences in speech-in-noise between listeners with sensorineural hearing impairment. This sensitivity gives confidence that the test would have been an appropriate tool to detect any differences in performance due to the presentation of air puffs with the current experimental set-up had there been any.

4.2 Conclusion

Previous research has found that aero-tactile stimulation influences the auditory perception of isolated components of speech stimuli in participants with normal hearing, however this was not found for open-set speech recognition performance on a sentence matrix test in participants with normal hearing (Derrick et al., 2016) or the participants in the current study with sensorineural hearing impairment. Due to the success of previous experiments, it is thought that auditory and aero-tactile integration of speech in a sentence format may still be possible following improvements to the current system used in this study (such as increased airflow) with refinements made based on further research into how skin responds to differing airflow patterns.

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Appendix A