Effects of Masking, and Sex on Lombard Vowel Production

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List of Abbreviations

BBN	Broadband Noise
CRM	Coordinate Response Measure
CVC	consonant+vowel+consonant
dB	Decibel
dB HL	Decibel Hearing Level
dB SPL	Decibel Sound Pressure Level
ED	Euclidean Distance
F0	Fundamental Frequency
F1	First Formant Frequency
F2	Second Formant Frequency
FFT	Fast Fourier Transform
Hz	Hertz
kHz	Kilohertz
LE	Lombard Effect
LPC	Linear Predictive Coding
LSVT	Lee Silverman Voice Technique
LTSS	Long-Term Speech-Shaped Noise
RMS	Root Mean Square

SD	Standard Deviation
SNHL	Sensori-neural hearing loss
SNR	Signal-to-Noise Ratio
SSN	Speech-Shaped Noise
TTB	Two-talker Babble
VOC	Cochlear Implant Noise Vocoder
VOT	Voice Onset Time

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Abstract

The change a speaker makes in response to background noise is known as the Lombard Effect (LE). This study investigated the acoustic changes that are undergone in the presence of broadband noise and two-talker babble. Of particular interest were vocal fundamental frequency (F0) and formant frequency vowel space measures across sex. Forty participants (20 male, 20 female) were recruited and asked to read phrases in quiet and in the presence of two-talker babble and broadband noise. These masker conditions were presented at 50 and 70 dB HL. The phrases were recorded and acoustically analysed. The results showed a significant sex difference for both F0 and vowel space. A masking condition effect was not displayed for either F0 or vowel space. A significant effect was however shown for F0 according to intensity level, suggesting a LE. While the sex difference in F0 values can be explained on the basis of differences in vocal anatomy, the sex difference in vowel space was indicative of a sociophonetic influence on speech production.

Introduction

Lombard Effect

In noisy environments, speakers change the way they speak. This was first reported by the French otolaryngologist Étienne Lombard, in 1911, who noticed those with a hearing loss, and those in a noisy environment, raise their voices "abnormally" (Lombard, 1911). Lombard asked individuals with normal hearing, and unilateral or bilateral deafness to read a simple text while playing noise to each ear, and also in a quiet setting. He concluded that the normal hearing person was "suddenly transformed into a bilateral deaf person" due to an increase in vocal intensity with noise, and returning to normal without noise (Lombard, 1911). Lombard also noted the individual seemed unaware of the alterations in his speech. The bilaterally deaf person showed no change in speaking behaviour. The unilaterally deaf person also showed no change when sound was applied to the impaired ear. When noise was delivered to the non-impaired ear, Lombard (1911) observed the same effect as with a normal hearing person.

This modification noted by Lombard (1911) has since been referred to as the Lombard Effect (LE). The LE is thought to be a subconscious, or passive, (Garnier, Henrich & Dubois, 2010; Lu & Cooke, 2009; Pick, Siegel, Fox, Garber, & Kearney, 1989) modification to increase intelligibility for the listener and to monitor one's own speech (Castellanos, Benedí & Casacuberta, 1996; Lombard, 1911). The present research was designed to further explore features of LE in female and male speakers.

Noise and Masking

Many communicative interactions take place in noisy environments and most often this noise does not interfere with the ability to communicate effectively. However, when attempting to communicate in the presence of loud noise, this noise can serve to mask the speech signal and subsequently interfere with communication. Auditory masking occurs when the perception of one sound is affected by the presence of another sound (Moore, 2004). Auditory masking in the frequency domain is known as frequency (or spectral) masking and auditory masking in the time domain is known as temporal masking. According to Brungart (2001), and Brungart, Simpson, Ericson and Scott (2001) two common types of frequency masking used in speech perception research are energetic, and informational masking.

Energetic masking is the more traditional and well-researched form of frequency masking in which competing signals (target and masker) contain energy in the same temporal and critical bands so that portions of one or both signals are rendered inaudible. The masking produced by broadband noise is an example of energetic masking. Broadband noise is a masking sound that contains frequencies across the range of human hearing in equal amplitude. This noise can be filtered to provide energy at a more limited range. Informational masking is a form of frequency masking which occurs when both the target signal and masker are audible but the listener is unable to separate the elements of the target as the masker sounds so similar. The masking produced by a competing speaker can be an example of informational masking, although it can also contain energetic masking.

Formant Frequency and Vowel Space

Two features of vowel production that allow a listener to differentiate vowels are vocal fundamental frequency (F0) and formant frequencies. The F0 is the lowest frequency component of voice, while the formant frequencies relate to the acoustic resonance of the vocal tract (Borden, Harris, & Raphael, 1994). Formant frequencies provide the dimensions for how open or closed, and front or back a vowel is articulated. The acoustic information provided by the first two formants (F1 & F2) is typically enough to allow a listener to differentiate one vowel from another. The lowest formant frequency is referred to as the first formant frequency (F1). It has a higher frequency for open vowels (such as /a/) and a lower frequency for closed vowels (such as /i/ or /u/). The second formant (F2) has a higher frequency for front vowels (/i/) and a lower frequency for back vowels (/u/) (Borden et al., 1994).

Acoustic vowel space is a quantitative measure which involves plotting corner vowels, such as /i/, /u/ and /a/ in an F1/F2 plane, to produce a three-sided vowel triangle. Several previous studies of speakers with normal and disordered speech have employed this measure, and have shown a significant correlation between acoustic vowel space and speech intelligibility (Kaipa, Robb, O'Beirne, and Allison, 2012; Turner, Tjaden & Weismer, 1995; Whitehill & Chau, 2004). For example, studies by Blomgren, Robb and Chen, (1998), Robb and Chen, (2008), and Kaipa et al., (2012) have shown that in difficult speaking circumstances, such as stuttering or glossectomy, the total vowel space decreases. This decrease in vowel space has been interpreted to reflect imprecise articulation, and leads to misunderstanding by listeners. It is possible that similar changes in vowel space would be evident for speech produced in the presence of a noisy environment.

Lombard Effect: Speech Perception

Research suggests that speech produced in the presence of noise (i.e., Lombard speech) is more intelligible than speech produced in quiet. One of the initial studies of this sort was conducted by Dreher and O'Neil (1957). The researchers asked 15 speakers to read spondee words and air traffic control sentences in the presence of white noise at varying intensity levels. This noise was presented through headphones and included conditions of quiet (to act as a baseline), 70, 80, 90, and 100 dB. The speech samples were audio recorded without noise but wideband noise was added post-recording to produce a constant speech-to-noise ratio. This recording was then played to 200 air force cadet listeners who were required to write what they heard. The results indicated that the greatest increase in intelligibility occurred with the introduction of the first noise condition (70 dB) with an increase of 35% intelligibility of spondee words and 27% of sentences from the speech produced in quiet. The more intense noise conditions maintained a stable intelligibility from the first increase. The results indicated that speech produced in the presence of noise becomes more intelligible as the masking noise becomes more intense - to a point. The study also noted other changes such as a jump in intensity of voice (approximately 5 dB) with presentation of the first masking level and then gradual increases of approximately 1 dB and a similar pattern in relation to increased duration.

A later study by Summers, Pisoni, Bernacki, Pedlow and Stokes (1988) supported the findings of Dreher and O'Neil (1957). These researchers audio recorded two male speakers reading digits zero through nine in quiet and under the condition of 90 dB SPL of broadband white noise. Similar to Dreher and O'Neil, these digits were recorded without noise but broadband noise was added for perceptual analysis. Different SNRs (-5, -10, and -15) were used through changing the intensity of the stimulus and maintaining 85 dB SPL of noise. A total of 41 listeners were presented with 200 samples (100 each from the quiet and 90 dB SPL conditions) through headphones and asked to identify the digits heard. The results showed that digits produced in 90 dB SPL of masking noise were consistently identified more accurately. Furthermore, as the SNR of the presented stimuli decreased, there became a more significant effect of masking noise. That is, as SNR decreased, digits produced under 90 dB SPL of masking were more identifiable than those produced in quiet. To evaluate the consistency of these effects, the authors repeated this perceptual experiment using digits produced under 100 dB SPL of broadband white noise. This time 29 listeners identified the digits under the same SNR conditions and the results replicated the initial experiment.

Liu and Kewley-Port (2004) studied the effects of long-term speech-shaped noise (LTSS) and multi-talker babble, and SNR values on the threshold at which vowels can be discriminated. One female speaker was recorded saying seven different vowels embedded in a /bVd/ syllable. This vowel was then isolated and the formant frequencies manipulated (increased by 0.7% to 17% over 24 steps). LTSS and multi-talker babble maskers (12-talker babble) were then added to the vowels at different SNRs and played to six listeners. Each set played to the listener contained the target vowel followed by two choices, one choice being the same as the target vowel, and one was the manipulated vowel. In assessing this over three conditions (quiet, LTSS, and multi-talker babble), the researchers were able to distinguish the threshold for being able to identify the target vowel. They found that (1) higher formant frequencies significantly increased threshold, (2) masking noise significantly degraded formant discrimination, (3) thresholds were elevated for low SNRs compared to quiet, and (4) LTSS noise was a more effective masker than babble, suggesting listeners may make use of the temporal variability in babble.

Cooke, Barker, Cunningham and Shao (2006) created a Grid corpus to evaluate speech perception in the presence of masking noise. The corpus consists of six-word sentences, such as "Lay green with A4 now", to be used as a competing talker or babble noise (Cooke et al., 2006). Lu and Cooke (2008) used this corpus to evaluate perception of Lombard speech. The stimuli used for the perception task were five sets of 100 utterances, corresponding to speech produced in quiet, in a background of a competing talker at levels of 82 and 96 dB SPL, and in a background of stationary noise at 82 and 96 dB SPL. These samples were normalised to have equal RMS energy and mixed with a speech-shaped noise masker or competing speech at an overall SNR of -9 dB. A group of 12 listeners were played the samples over headphones and asked to identify in each utterance the letter and digit keywords. Results showed that for the conditions produced in the presence of noise there was a statistically significant increase when compared to those produced in quiet. The study demonstrated that speech produced in the presence of noise was more intelligible than speech produced in quiet, and it becomes more intelligible with increasing noise intensity. Speech produced in the presence of speech-shaped noise appears to produce more intelligible speech than that produced in competing speech. Presumably, the linguistic content of the competing speech signal serves to interfere with normal speech production.

Cooke and Lecumberri (2012) studied the effect of Lombard speech in noise and in quiet for Spanish learners of English. A total of 48 listeners were asked to identify the alpha-numeric keyword in a random selection of phrases taken from the Grid corpus (Cooke et al., 2006). These phrases were spoken by four female and four male talkers in quiet and in the presence of speech-shaped noise (SSN), at 82 and 96 dB SPL, delivered over headphones. The stimuli were audio recorded and presented to listeners in quiet and with SSN added at SNRs of 0, -5, and -9 dB. The results show a clear intelligibility gain for speech produced in the presence of maskers compared to speech produced in quiet for the Spanish listeners. This was compared to the previous study (Lu and Cooke, 2008) in which similar speech was presented to native listeners. This comparison showed that for speech produced without noise and added to -9 dB SNR of SSN the effect for native and non-native listeners is similar, while for Lombard speech it seems native listeners are more advantaged than non-native listeners. The perceived benefit of Lombard speech for non-native listeners was dependent on noise level. As SNR increased the relative benefit decreased and disappeared altogether at 0 dB SNR. When no noise was added to Lombard speech, the speech was less intelligible than speech produced without the presence of noise (or normal speech).

There is a small body of research which suggests that informational masking has a larger (negative) effect over energetic masking on speech perception (Brungart, 2001, Brungart et al., 2001). For example, Brungart (2001) examined the effect of informational and energetic masking in the perception of spoken phrases. This was done by masking pre-recorded phrases with maskers of another speaker, and for two types of noise maskers, Gaussian noise, and speech-shaped noise, at different SNR values. The phrases consisted of those taken from the coordinate response measure (CRM) speech corpus for multitalker communications research (Bolia, Nelson, Ericson, & Simpson, 2000). In the speech-masker condition the target phrase included the call sign "Baron", while the masker phrase included a call sign other than "Baron". The speaker of both target and masker were randomized to include different combinations of sex and voice similarity. The samples were presented to nine listeners who were required to identify the number-colour stimulus of the target phrase. Brungart theorised that in the case of competing speakers, if energetic masking had a significant effect on interpretation, the participants would choose random responses when unable to decipher the target. He found, however, that an overwhelming number of incorrect responses were the phrases spoken by the competing talker. This shows the strong negative effect of informational masking. Brungart found that influence of the speaker’s voice significantly influenced perceived speech intelligibility, whereby the more similar the masker was to the target (e.g., same sex), the less intelligible the target. Identification scores with an energetic noise masker decrease monotonically with decreasing SNR, while SNR has a smaller effect on scores. Brungart found that listeners were consistently more accurate in the perception of phrases in the presence of an energetic masker than informational masking, regardless of changes in the SNR. That is, energetic masking was less effective (distracting) than informational masking.

Brungart et al. (2001) conducted an experiment similar to the Brungart (2001) study but with 3-4 competing talkers instead of just one competing talker. The results of this experiment showed that performance was generally better when the target and masker are qualitatively different (e.g. different sex), and worse when the masker and target are the same speaker. This shows the degradation effect of informational masking. Performance tended to decrease when the level of the target was reduced relative to the maskers. In most conditions, performance improved when the participants were exposed to the target characteristics prior to presentation. The researchers suggested that the influence of a competing linguistic message that occurs with an informational masker serves to further obscure the ability to perceive speech.

Lombard Effect: Speech Production

There is a body of research that has acoustically examined the changes in speech production that occur to speakers under the presence of a LE. Features that are often examined include changes to speech amplitude, duration, F0, F1, and F2 frequencies.

Summers et al. (1988) studied two male participants producing single words in quiet, and with varying intensity levels of filtered broadband noise. The 15 stimulus words consisted of Air Force speech recognition vocabulary such as digits zero through nine and control words such as "enter". The participants wore headphones throughout the duration of the experiment and their speech was audio recorded. The stimulus words were randomly generated to produce lists of 15 words which the participants read under four noise conditions (quiet, 80, 90, and 100 dB SPL) five times. These 300 samples from each participant were then acoustically analysed using linear predictive coding (LPC) and cursor controlled displays, to provide amplitude, duration, F0, F1 and F2 frequencies. The researchers found that noise had a significant effect on each of these acoustic measures. Each increase in masking level led to an increase in amplitude, while duration and F0 showed an increase between the quiet and 80 dB SPL condition but lesser changes across the more intense masking. The mean F1 frequency increased in response to increasing noise for one participant but remained relatively the same for the other. TheF2 frequency did not change significantly across either participant.

Junqua (1993) investigated sex differences in speakers communicating in the presence of white-Gaussian noise. Forty-nine words (alphanumeric and control) were recorded in quiet and in 85 dB SPL of white-Gaussian noise using headphones. These words were recorded twice under each condition by each on the 10 speakers (five males & five females). The author performed an acoustic-phonetic analysis to examine changes occurring under the influence of a LE. In particular, formant frequencies, spectral energy, F0 and duration were examined. There was large interspeaker variability. However, it was noted that energy increased in certain bands and that this trend was more noticeable in females, suggesting that females tend to increase vocal effort more so than males. On the other hand, F0 was found to increase for male speakers but no such change was found for the female speakers. This was thought to be due to a ceiling effect in which females voices are already more high-pitched. Both males and females showed an increase in F1 for vowels, glides, liquids, and nasals, however this increase was more evident for the female speakers. A similar trend for females was found for F2. Both sexes showed an increase in word duration due to an increase in vowel duration and a lesser increase in the duration of consonants. No reason was given for the various sex differences observed, however there are past acoustic studies which suggest that sex differences in various parameters of speech production (e.g., voice onset time) may be due to a conscious manipulation of speech patterns to overtly or tacitly convey gender identity (Cheshire, 2002). Byrd (1994) and others (Robb, Gilbert & Lerman, 2005) report that females and males differ in their general pattern of pronunciation, with females tending to use more carefully articulated speech and adopt this speaking style in experimental settings. There have been no direct attempts to determine whether sex differences associated with the production of speech and LE may be socially motivated.

More recently, Patel and Schell (2008) examined the influence of linguistic content on LE speech in a sample of 16 participants. Eight males and eight females took part in an interactive computer game in speaker-listener pairs. Each participant in the pair was placed in separate rooms and were each exposed to three noise conditions; quiet, 60 dB SPL, and 90 dB SPL of multi-talker noise. The speaker communicated via a headset microphone and the task of the game was for the speaker to instruct the listener to perform a series of actions on the screen. A total of 30 utterances were elicited in each of the noise conditions and the words used in these utterances were grouped according to linguistic content. Similar to the results of Summers et al. (1988), changes were found to occur in speech intensity, duration and F0 as a function of increasing noise-level. The duration of syllables increased significantly across noise types and this was the same for males and females. The syllabic duration of word type was also significant and content words (e.g., agents, objects, and locations) were elongated compared to function words (e.g., articles, prepositions). Sex did not have an effect on F0 but significant increases were noted for noise type and word type. The F0 for agent words (e.g., the name of the dog in the game) tended to increase most. Intensity significantly increased with noise and word type but no sex differences were found for peak intensity.

Lu and Cooke (2008) evaluated the effect of noise on speech production. Eight participants were asked to read a set of 50 sentences while listening to various numbers of talker-babble maskers. The number of talker-babble maskers ranged from a single speaker, to infinite speakers, also known as speech-shaped noise, ($N = \{1, 2, 4, 8, 16, \infty\}$). Each N-talker babble was presented at 89 dB SPL. Single speaker (N=1) and speech-shaped noise ($N = \infty$) were presented at 82 and 96 dB SPL as well as 89 dB SPL. There was also a quiet condition in which no noise was played through the headphones. These various maskers equated to 11 different listening conditions. The sentence duration, RMS energy, F0, and spectral centre of gravity was determined. A significant increase in RMS energy and F0, and a lesser increase in other measures, was found. The F1 frequency was found to increase with masking but more so for the speech-shaped noise than competing talkers.

Lu and Cooke (2009) investigated whether there may be an active component to speech associated with the LE. That is, they examined the possibility that the changes made to an individual's speech productions depend on the type of masking noise. The researchers suggested that a speaker may make purposeful modifications to increase intelligibility for their listener in the presence of background noise and that this changes with how noise is filtered. They investigated this hypothesis through gathering oral reading samples produced in quiet, full-band, low-pass filtered, and high-pass filtered noise. Acoustic analysis of RMS energy, F0, and F1 frequency was performed. Results showed that for all conditions relative to quiet, the acoustic parameters increased. The high-pass conditions resulted in significant increases in all parameters relative to quiet but these increases were significantly smaller than the full-band condition. In the low-pass conditions little difference was found between these conditions and full-band noise. This has a positive effect for listeners in the low-pass condition but increases masking in the high-pass condition making speech more difficult to understand. The researchers concluded that the LE does not have an active component through which speakers modify their speech to increase intelligibility in different noise types, at least for read speech.

Cooke and Lu (2010) studied the effect of different background noise on speech production. They used eight British English speakers, both alone, and also paired by gender. The speakers were required to solve a Sudoku puzzle aloud under quiet, competing speech, speech-shaped noise, and speech-modulated noise at 82 dB SPL. The speech by four of the speakers that was recorded in quiet was then modified and used as the maskers for the masking parts of the study. Results showed that measures of word duration, RMS energy, and F0 increased in response to noise relative to quiet. Communicative intent (i.e., when the participants were paired) also led to significant changes in speech acoustics, relative to the alone participants. When these results were compared to the quiet baseline however, it was found that for both alone and paired participants, the extent of changes made to speech were no different. Speech-shaped noise was shown to induce the largest increases in speech production. They concluded that with read speech it is largely the energetic masking component of the noise that is responsible for Lombard changes. To understand whether speakers actively change their Lombard speech to increase intelligibility, vowel dispersion was examined. Vowel space for four vowels was calculated in each of the noise conditions and across the two tasks. Compared with non-communication, the communicative task showed a larger vowel dispersion in quiet and speech-modulated noise but produced similar values for competing speech and speech-shaped noise. None of the three noise backgrounds led to significant changes in vowel dispersion for the communicative task and only speech-shaped noise differed from quiet in the non-communication task. This demonstrates a mixed effect of noise and task on vowel space with the communicative task leading to more contrast in vowel space in two of the four noise backgrounds. Future research is needed to examine whether acoustic changes in speech occur in the presence of differing noise backgrounds.

Hazan and Baker (2011) used 40 speakers to study the acoustic changes to speech that occur under the influence of babble noise (it is not known how many speakers contributed to the babble noise) compared to a simulated cochlear implant listening condition. The participants were paired according to sex and asked to participate in a game of spot-the-difference. The pictures used for the game had differences that would encourage elicitation of 36 keywords. The participants were in different rooms during the game and communicated via headsets. Participants completed the task in good listening conditions (quiet) and then the voice of one speaker was processed via a three-channel noise vocoder (VOC), and babble, before the listener heard it. In this study it was the listeners' speech changes that were of interest. The participants were also asked to read sentences and name pictures individually. The speech sets were then transcribed and analysed in terms of F0 median and range, mean word duration, mean energy in the 1-3 kHz range of the long-term average spectrum of speech, and vowel space. Results showed that median F0 was higher during clear speech than in speech produced under challenging listening conditions, while men also had a larger F0 range in clear speech rather than more difficult speech compared with women. There were no sex differences for F1 frequency, however females had a larger F2 range for conversational speech compared to males. For both sexes, there was a greater difference in F1 range for read speech than conversational speech. In the VOC condition where changing parameters is unlikely to aid listeners, speakers did not change F0 median and range and other increases were less than what was seen in the babble condition. Based on these results it was hypothesised that speakers change the way they speak depending on the listeners' needs, even when their own listening environment is not challenging.

Statement of the Problem

The Lombard Effect (LE) is the modification made to speech production when speaking in noise (Lombard, 1911). Since its discovery, many perceptual and production studies have been carried out to determine changes that are made to speech when produced in noise, how this affects intelligibility, and what types of masking noise differentially influence the LE. Past perceptual research has suggested that acoustic features of vowels, namely F0, F1 and F2 frequency are relied upon more in noisy conditions (Parikh & Loizou, 2005; Swanepoel, Oosthuizen, & Hanekom, 2012). Furthermore, perception of speech under conditions of informational masking is more negatively affected compared to energetic masking. Presumably, the linguistic information that is included as part of an informational masker further obscures the ability to perceive speech (Brungart, 2001, Brungart et al., 2001).

Past research examining the speech production characteristics associated with the LE have found changes in a variety of acoustic parameters such as speech duration, F0 and formant frequencies. There have been limited attempts to directly compare the influence of differing noise such as broadband noise and babble on speech production, although Cooke and Lu (2010) have suggested that evidence for vowel space and formant frequency changes in background noise is mixed. Similar to the suggestions offered for the differential effects of different noise on speech perception, the same may hold true for speech production. That is, the competing linguistic message associated with babble masking may influence (positively or negatively) speech production compared to broadband noise.

Finally, there have been no attempts to explore possible sex differences in speech production that occur under different noise backgrounds. Past acoustic research has suggested a possible sociophonetic influence on speech production (Cheshire, 2002); rather than sex differences based on anatomical and physiological features of the vocal tract. Sociophonetic influences in speech production presumably convey gender identity. This is particularly evident in experimental settings, where females tend to use more carefully articulated speech compared to males. Past LE research indicating a sex difference in speech production may therefore reflect a sociophonetic influence, whereby the differences in speech production shown between males and female cannot be accounted for on the basis of vocal anatomy.

The purpose of this study was to examine acoustic features of vowel production in females and males under the influence of broadband noise and two-talker babble. The following research questions were posed:

1. Is there a significant sex difference in F0 in speech produced in quiet, in the presence of two-talker babble at varying intensity levels, and in the presence of broadband noise at varying intensity levels?
2. Is there a significant difference in F0 in speech produced in quiet, in the presence of two-talker babble at varying intensity levels, and in the presence of broadband noise at varying intensity levels?
3. Is there a significant sex difference in vowel space in speech produced in quiet, in the presence of two-talker babble at varying intensity levels, and in the presence of broadband noise at varying intensity levels?

4. Is there a significant difference in vowel space in speech produced in quiet, in the presence of two-talker babble at varying intensity levels, and in the presence of broadband noise at varying intensity levels?

Method

Participants

A total of 40 adults took part in this study. The participants were recruited from within the student body at the University of Canterbury community, their respective friends and family, by word-of- mouth, and through public advertisement of the study. The participants included 20 males (*M* age = 25-years) and 20 females (*M* age = 24;5-years) with an overall age range of 20-39 years. Inclusion criteria for participation in this study included (1) aged between 20 and 40 years, (2) passing a hearing screening at the frequencies of 0.5, 1, 2, and 4 kHz, and (3) native, fluent speakers of New Zealand English. Data about the individual participants can be found in Table 1. The study received prior approval from the University of Canterbury Human Ethics Committee (see Appendix 1). All participants volunteered for the study and provided written consent (see Appendix 2). Upon completion of the tasks required for the study the participants were reimbursed for their time with a $20 grocery voucher.

Table 1: Sex (F=female, M=male), age (years months), and audiometric thresholds for right (R), and left (L) ears for each participant (1-20 F, 1-20 M).

Sex	500Hz		1kHz		2kHz		4kHz		Age
	R	L	R	L	R	L	R	L	
F1	5	15	5	20	-5	5	-5	5	39,1
F2	-5	-5	0	-5	5	-5	5	-5	21,7
F3	5	5	0	5	10	5	-5	0	21,8
F4	5	0	0	0	-5	5	10	10	22,6
F5	10	10	10	10	0	0	0	0	23,1
F6	5	5	5	5	15	15	-5	-5	23,6
F7	5	5	5	5	5	5	10	10	22,5
F8	0	5	0	0	5	0	15	5	24,0
F9	5	5	-5	0	5	5	0	-5	23,3
F10	5	5	5	0	0	5	5	5	24,8
F11	5	0	10	0	10	5	5	10	23,11
F12	5	5	5	0	5	10	5	15	23,5
F13	10	10	0	0	5	-5	5	0	21,8
F14	5	0	10	10	5	5	5	0	24,3
F15	5	10	-5	0	15	0	0	0	24,5
F16	5	5	5	10	10	15	5	15	23,10
F17	10	5	5	5	5	5	5	0	23,11
F18	5	5	5	5	0	0	5	0	24,2
F19	0	5	0	-10	5	-10	10	-5	31,6
F20	10	15	0	5	5	10	0	5	23,11
M1	-5	0	-5	5	0	10	10	20	23,5
M2	-5	5	-5	0	-5	5	-10	5	32,2
M3	5	5	5	5	5	5	5	10	33,5
M5	0	5	0	5	5	5	15	15	22,6
M6	5	5	-5	-5	-5	0	5	-5	24,1
M7	0	5	10	5	10	5	5	10	23,6
M8	5	5	5	5	5	5	5	5	24,2
M9	10	5	0	5	5	5	-5	10	23,5
M10	5	0	5	5	10	5	10	10	24,1
M11	10	10	10	5	5	0	5	5	21,9
M12	0	5	-5	5	0	-5	0	-5	21,10
M13	10	10	5	10	0	0	0	5	23,8
M14	10	5	10	5	5	5	5	5	23,7
M15	15	15	15	10	15	5	15	5	23,11
M16	5	5	5	5	5	5	5	5	20,1
M17	5	10	10	5	10	10	10	5	24,3
M18	5	0	0	0	5	5	0	5	21,11
M19	0	5	5	0	5	5	5	0	27,8
M20	10	5	10	0	20	0	20	5	32,11

Stimuli

Masking Noise.

Two types of noise stimuli were created for the study. The stimuli consisted of broadband noise and two-talker babble. The broadband noise was created using a custom program in MatLab and Adobe Audition and was lowpass-filtered at 8 kHz. The two-talker babble was created using the Grid Corpus (Cooke et al., 2006), which has been used in similar studies (Lu & Cooke, 2008, Lu & Cooke, 2009, Cooke & Lu, 2010) and can induce linguistic bombardment. Speakers 2 (male speaker) and 4 (female speaker) were selected from the Grid Corpus to create babble stimuli. A specifically designed MatLab program was created to generate a10-minute sample of two-talker babble with between-phrase pauses removed. Spectra displaying the average amplitude across the frequency range of both two-talker babble and broadband noise can be found in Figure 1.

In total, five listening conditions were used for this study. Two broadband noise (BBN) conditions were presented at intensity levels of 50 and 70 dB HL, and two-talker babble (TTB) was also presented at intensity levels of 50 and 70 dB HL. There was also one "quiet" condition in which no noise was presented. These intensity levels selected for the study correspond with those used in previous studies (e.g., Cooke & Lu, 2010; Garnier et al., 2010; Junqua ,1993; Lu & Cooke, 2008; Summers et al., 1988) and provides a range of masking levels known to induce LE changes to speech production. The intensity of all masker waveforms were normalised to have the same RMS amplitude before they were saved to a CD. A calibration track containing a 1000 Hz tone with the same RMS amplitude as the maskers was also saved to the CD. This calibration track was used to adjust the gain of the speech channel of an audiometer before each participant. Once this was done, the actual intensity levels could be set using the normal audiometer controls.

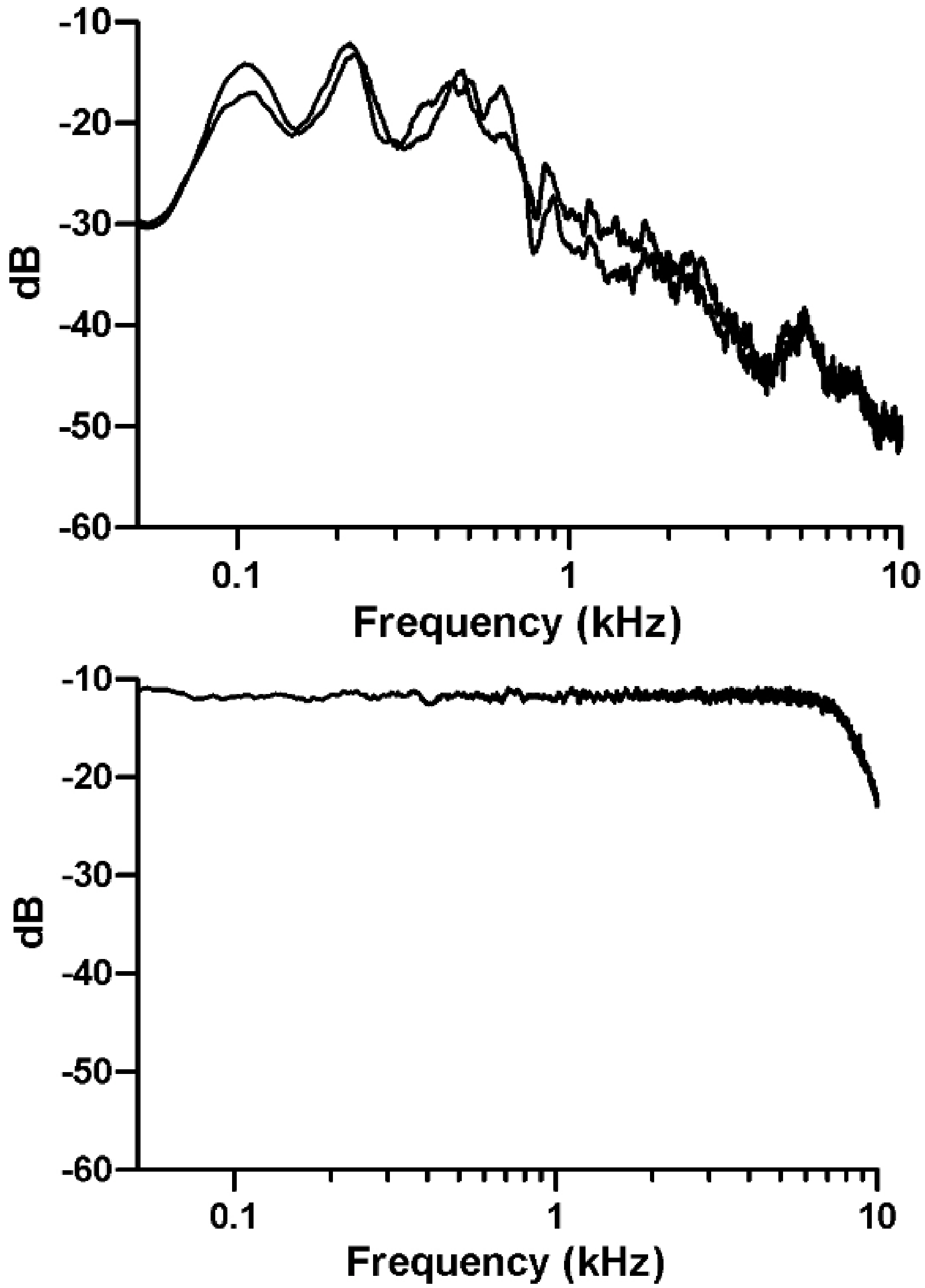

Figure 1: Spectra displaying average amplitude at each frequency for two-talker babble (above) and broadband noise (below). Two-talker babble displays two spectral estimates to show variation in individual samples but the overall average is the same.

Speech Stimuli

The speech samples consisted of consonant+vowel+consonant (CVC) syllables. The prevocalic consonant consisted of a stop consonant /p,t,k,b,d,g/. Stop consonants were selected to allow for easy acoustic identification of vowel onset. Each consonant was paired with the vowels /i,u,a/. These vowels were selected to sample vowel space because of their articulation at extreme locations within the vocal tract. The phoneme /t/ was used as the post-vocalic consonant for each to syllable. Each CVC syllable was produced once in each of three different carrier phrases to obtain three samples of each syllable. The three phrases were, "*I saw CVC today*," "*I put a CVC in there*," and "*Say CVC again*." The cards used to elicit the target phrases can be found in Appendix 3. In total a set of 54 CVCs (6 stop consonants x 3 vowels x 3 phrases) were sampled in each of the five listening conditions.

Procedures

Each participant was required to read each phrase aloud (54 in total) for each of the seven listening conditions. These phrases were placed on index cards with a picture to cue pronunciation of the vowel. The order of the phrases, as well as the order of listening conditions was randomised for each participant. Each participant wore supra-aural headphones (Telephonics 296 D200-2) which remained in place over the participants ears throughout the duration of the experiment. Participants wore the headphones during the quiet condition as well. This was to ensure the occlusion effect remained stable across participants and to ensure that own-voice masking remained constant (Cooke & Lu, 2010). Instructions for this study were not scripted however, each participant was told to talk "as if they were speaking to someone over the noise".

At the beginning of each listening condition and intensity level, participants were required to read aloud the first paragraph of the Rainbow Passage (Fairbanks, 1960), found in Appendix 4. The passage consists of 101 words. This task was assumed to allow the participants to become acclimated with the particular listening condition. Upon completion of the Rainbow Passage, each participant read aloud the set of CVC (phrase) productions. The participant produced each of the phrases at their own pace. After each noise condition the noise was turned off and the participant engaged in a brief conversation with the examiner to provide a break and reset talking level.

Noise level and presentation of masking was controlled via a GSI 61 clinical audiometer with input from a portable DVD player (Philips, PO9030/79). The speech samples were recorded via a digital voice recorder (Olympus WS-750M) positioned approximately 50 cm away from the participant's mouth. The researcher and audiometer were positioned outside the sound booth but the researcher was visible through a glass window of the booth. Communication and instruction was provided through the "talk-forward" function of the audiometer.

Acoustic Analysis

Each phrase production was converted to a *wav* file and submitted to acoustic analysis using custom software written in MatLab. This software allowed time markers to be placed on the file and then retrieved these time markers to segment the phrase and isolate the vowel portion of the CVC. The vowel portion of the CVC syllable was measured for F0, F1 and F2 frequencies. A pair of vertical cursors was placed at vowel onset and offset, respectively. The fast Fourier transform (FFT) and linear predictive coding (LPC) spectra were then displayed and cursors demarcated the location of F1 and F2. Once the segmentation was completed, the MatLab software automatically determined F0, F1 and F2 frequency. These numeric results were then exported to an Excel file and organised according to vowel and noise condition for each participant.

Vowel Space Analysis

The procedures for determining vowel space were similar to those used by Kaipa et al. (2012). The median F1 and F2 values collected for each vowel during each listening condition were used to calculate vowel space. The absolute value of the vowel space area does not possess functional significance, although it serves as a general pattern of change in vowel space area (Turner et al., 1995). The formula used to calculate vowel space was based on calculating the Euclidean distance (ED) between each vowel pairing (/i/, /u/, /a/). The specific formula used for vowel space was as follows:

$$AREA_{iua} = 0.25 \times \sqrt{(ED_{ia} + ED_{iu} + ED_{ua})\,(ED_{ia} + ED_{iu} - ED_{ua})\,(ED_{ia} + ED_{ua} - ED_{iu})\,(ED_{ia} + ED_{ua} - ED_{iu})}$$

Statistical Analysis

The F0 and vowel space values obtained for each participant were collapsed across the three phrases. These values were then collapsed according to participant sex. A two-way analysis of variance (ANOVA) test was performed for F0 and vowel space. The within-groups factor was the five listening conditions (quiet, BBN50 dB HL, BBN70 dB HL, TTB50 dB HL, TTB70 dB HL) and the between groups factor was sex (male vs. female). Post-hoc *t*-tests were used to follow-up significant findings from the ANOVA tests.

Measurement Reliability

To assess reliability of the acoustic measurements, 5% of the original CVC vowel samples were randomly selected and re-measured by the researcher. Pearson Product-Moment correlation coefficients and absolute mean differences for measurement of F0, F1 and F2 frequencies between the first and second measurements were calculated. The correlation coefficients for re-measurement of F0, F1, and F2 were 0.992, 0.988, and 0.913, respectively.

Results

Fundamental Frequency

The F0 values were determined for each participant's production of each vowel across each listening level. A group analysis was performed by collapsing the F0 values across the three vowel types to obtain an overall F0 for each person. These overall individual F0 values were then further collapsed according to sex group. The mean F0 results for female and male participants are displayed in Figures 2 and 3.

Females

The average results of F0 for females for each listening condition are shown in Table 2. For the quiet condition individual F0 values ranged from 148 Hz to 241 Hz and averaged at 204 Hz. The broadband noise conditions ranged from 170 Hz to 239 Hz and averaged at 214 Hz for BBN50 and for BBN70 ranged from 187 Hz to 245 Hz and averaged at 224 Hz. The TTB50 condition had individual F0 scores ranging from 156 Hz to 234 Hz with an average of 211Hz, while the TTB70 conditions individual scores ranged from 198 Hz to 239 Hz with a group average of 223 Hz.

Males

The average F0 results for males are shown in Table 3. The quiet condition showed F0 values ranging from 102 Hz to 157 Hz with a group mean of 129 Hz. For the BBN50 condition, individual F0 values ranged from 117 Hz to 178 Hz with a group average of 147 Hz while the BBN70 condition showed individual F0 values ranging from 119 Hz to 238 Hz with a group mean of 171 Hz. The two-talker babble conditions resulted in F0 values ranging from 113 Hz to 208 Hz with a group mean of 145 Hz for the TTB50 condition, and values ranging from 109 Hz to 228 Hz with an average of 166 Hz for the TTB70 condition.

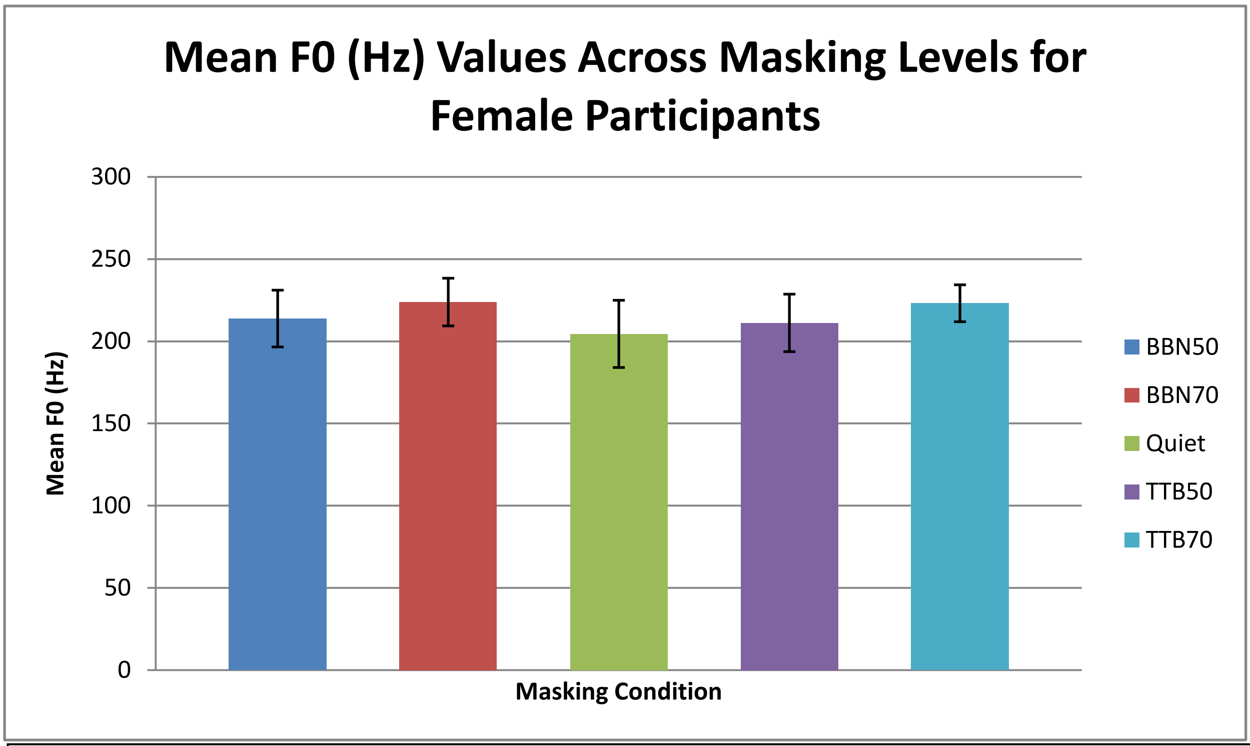

Figure 2: Mean fundamental frequency (F0) values for the female participants at the listening conditions, from left to right: broadband noise at 50 (BBN50), and 70 dB HL (BBN70), quiet, and two-talker babble at 50 (TTB50), and 70 dB HL (TTB70).

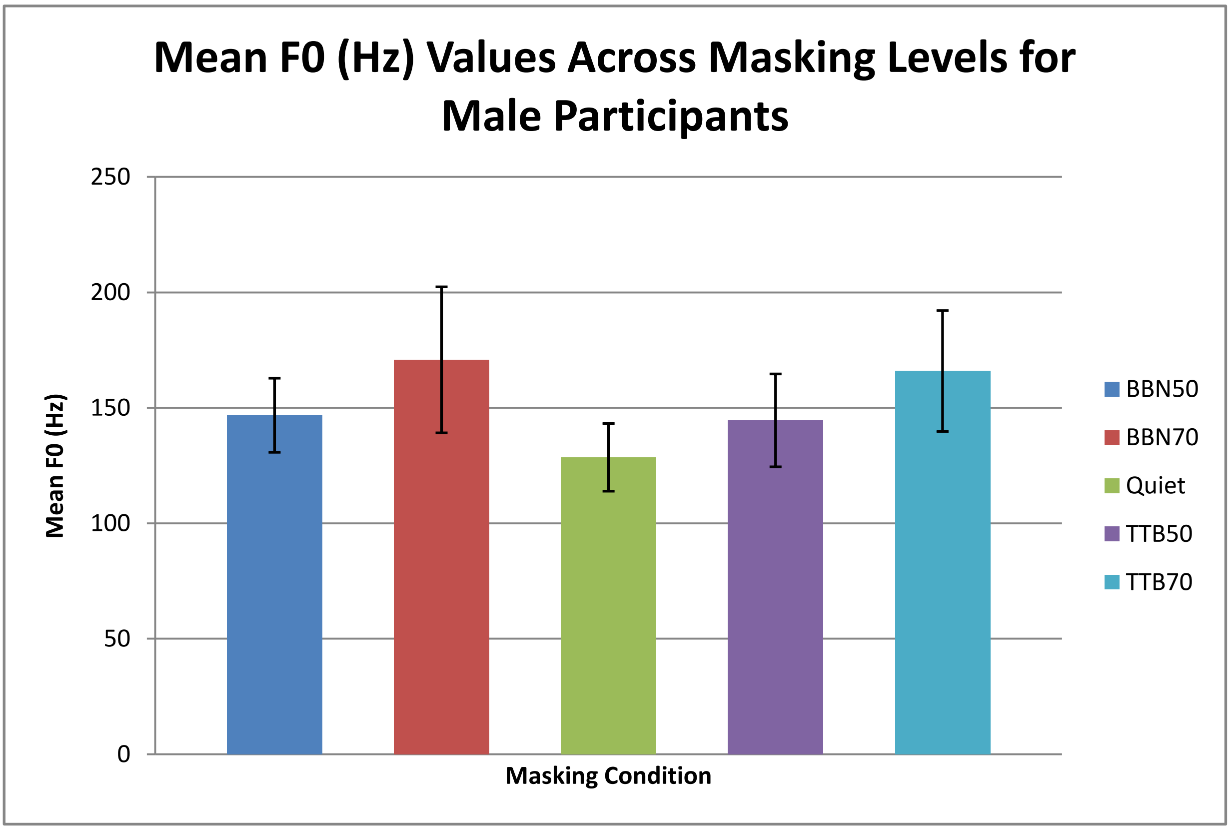

Figure 3: Mean fundamental frequency (F0) values for the male participants at the listening conditions, from left to right: broadband noise at 50 (BBN50), and 70 dB HL (BBN70), quiet, and two-talker babble at 50 (TTB50), and 70 dB HL (TTB70).

Table 2: Fundamental frequency (F0) values (in Hz) for the female (F) participants at the listening conditions of Quiet, Broadband masking at 50 (BBN50) and 70 dB HL (BBN70) as well as Two-talker babble at 50 (TTB50) and 70 dB HL (TTB70).

	BBN50	BBN70	Quiet	TTB50	TTB70
F1	169.7	223.9	148.1	155.7	197.9
F2	227.0	231.7	211.1	219.2	231.2
F3	239.2	211.3	180.4	209.6	223.5
F4	207.8	235.4	195.7	205.5	223.1
F5	190.3	207.1	215.5	204.2	216.6
F6	216.2	221.4	203.7	205.9	209.5
F7	216.8	231.2	210.6	216.1	221.9
F8	217.3	218.9	223.6	215.8	235.2
F9	215.6	187.3	215.2	215.6	209.4
F10	235.4	228.0	233.8	219.1	237.4
F11	210.2	227.2	204.5	219.7	220.1
F12	212.8	213.0	241.4	194.5	222.8
F13	232.4	245.5	181.8	231.3	227.3
F14	184.4	200.8	180.2	185.0	201.7
F15	226.9	244.4	203.1	233.7	236.0
F16	230.6	216.2	224.0	229.4	235.1
F17	210.2	236.2	212.4	199.9	238.7
F18	216.0	233.7	203.7	219.6	226.4
F19	222.3	223.5	204.9	219.6	222.8
F20	195.2	240.3	196.0	224.3	225.4
Mean	213.8	223.8	204.5	211.2	223.1
SD	17.3	14.5	20.4	17.5	11.2

Table 3: Fundamental frequency (F0) values (in Hz) for the male (M) participants at the masking conditions of Quiet, Broadband masking at 50 (BBN50) and 70 dB HL (BBN70) as well as Multi-talker babble at 50 (TTB50) and 70 dB HL (TTB70).

	BBN50	BBN70	Quiet	TTB50	TTB70
M1	142.9	156.3	134.6	147.6	163.1
M2	154.2	158.5	148.5	155.6	157.9
M3	132.8	146.5	119.0	144.3	154.2
M4	177.8	230.5	148.0	208.4	227.9
M5	140.7	125.0	119.9	126.5	144.5
M6	152.0	163.8	139.6	141.4	171.4
M7	151.3	146.3	126.3	160.5	190.3
M8	138.0	170.0	120.9	145.0	171.4
M9	156.9	184.0	125.9	137.5	167.9
M10	178.1	212.3	127.2	166.9	211.3
M11	135.9	166.2	136.4	132.0	153.0
M12	117.1	135.1	108.8	112.6	133.3
M13	123.1	119.0	117.7	126.2	109.0
M14	135.7	185.4	102.3	119.4	176.4
M15	150.8	237.8	126.5	146.2	193.9
M16	138.5	146.3	130.4	140.1	146.7
M17	130.8	171.5	125.3	132.7	147.4
M18	151.4	206.2	105.9	136.0	155.1
M19	169.2	187.1	157.2	162.5	182.0
M20	158.5	167.7	150.7	150.0	162.3
Mean	146.8	170.8	128.5	144.6	166.0
SD	16.0	31.6	14.6	20.1	26.2

Males vs. Females

To examine the difference in F0 between males and females a two-way ANOVA was performed. The within-groups factor was masking and the between-groups factor was sex. There was no significant interaction between masking noise and sex [$F(4,190) = 1.970$, $p = 0.101$]. The main effect for sex was significant [$F(1,190) = 496.040$, $p = 0.000$]. Not surprisingly, females were shown to have a significantly higher F0 than males. The main effect for masking type was also significant [$F(4,190) = 15.582$, $p = 0.000$] indicating a LE occurred for F0. Follow-up t-test, using the Tukey HSD test, identified significant differences between all possible comparisons with the exception of the BBN50 versus the TTB50 condition ($p = 0.984$) and between the BBN70 versus the TTB70 condition ($p = 0.973$). These results indicated that for both females and males, the lowest F0 values were found for the Quiet condition and the highest F0 values were found for the two loudest masking conditions (BBN70 & TTB70).

Vowel Space

The vowel space values were determined for each participant across each listening level. A group analysis was performed by collapsing the vowel space values according to sex group.

Females

The individual results of the vowel space areas for women are shown in Table 4. For the quiet condition the individual vowel space ranged from 12606 Hz^2 to 242251 Hz^2, and averaged 138825 Hz^2 for the group. The individual vowel space results for the BBN50 condition ranged from 61032 Hz^2 to 252904 Hz^2, with an average of 139639 Hz^2, while the results of BBN70 ranged from 91927 Hz^2 to 237663 Hz^2 with a group average of 139417 Hz^2. For the two-talker babble conditions, TTB50 ranged from 61830 Hz^2 to 256898 Hz^2, with an average of 140070 Hz^2, and the TTB70 condition for females ranged from 75163 Hz^2 to

338523 Hz^2, with a group average of 145862 Hz^2. The group vowel space results for the various listening conditions are shown in Figure 4.

Table 4: Vowel space values (in Hz^2) for the female (F) participants at the masking conditions of Quiet, Broadband masking at 50 (BBN50) and 70 dB HL (BBN70) as well as Two-talker babble at 50 (TTB50) and 70 dB HL (TTB70).

	BBN50	BBN70	Quiet	TTB50	TTB70
F1	84726	95434	99491	80026	95630
F2	193831	91927	153114	103551	133455
F3	252904	202911	238952	256898	209762
F4	101129	149999	12606	101978	127668
F5	206325	164279	139493	158235	158454
F6	85486	106379	73657	72506	75163
F7	103447	98138	141231	64417	127908
F8	61032	96827	58618	100556	102173
F9	194278	147975	195741	190995	149853
F10	142594	173690	233231	191898	338522
F11	147561	134490	132109	146341	83716
F12	180238	237663	206164	242308	233187
F13	154681	114291	242251	190379	168968
F14	98036	116816	128288	108473	115694
F15	88067	121271	106198	61830	116928
F16	175851	170145	114175	193902	208572
F17	142081	119503	128666	193559	135149
F18	127428	156964	124910	129825	119057
F19	157437	143770	166355	140969	139537
F20	95647	145858	81256	72753	77850
Mean	139639	139417	138825	140070	145862
SD	50353	38159	61548	59840	62750

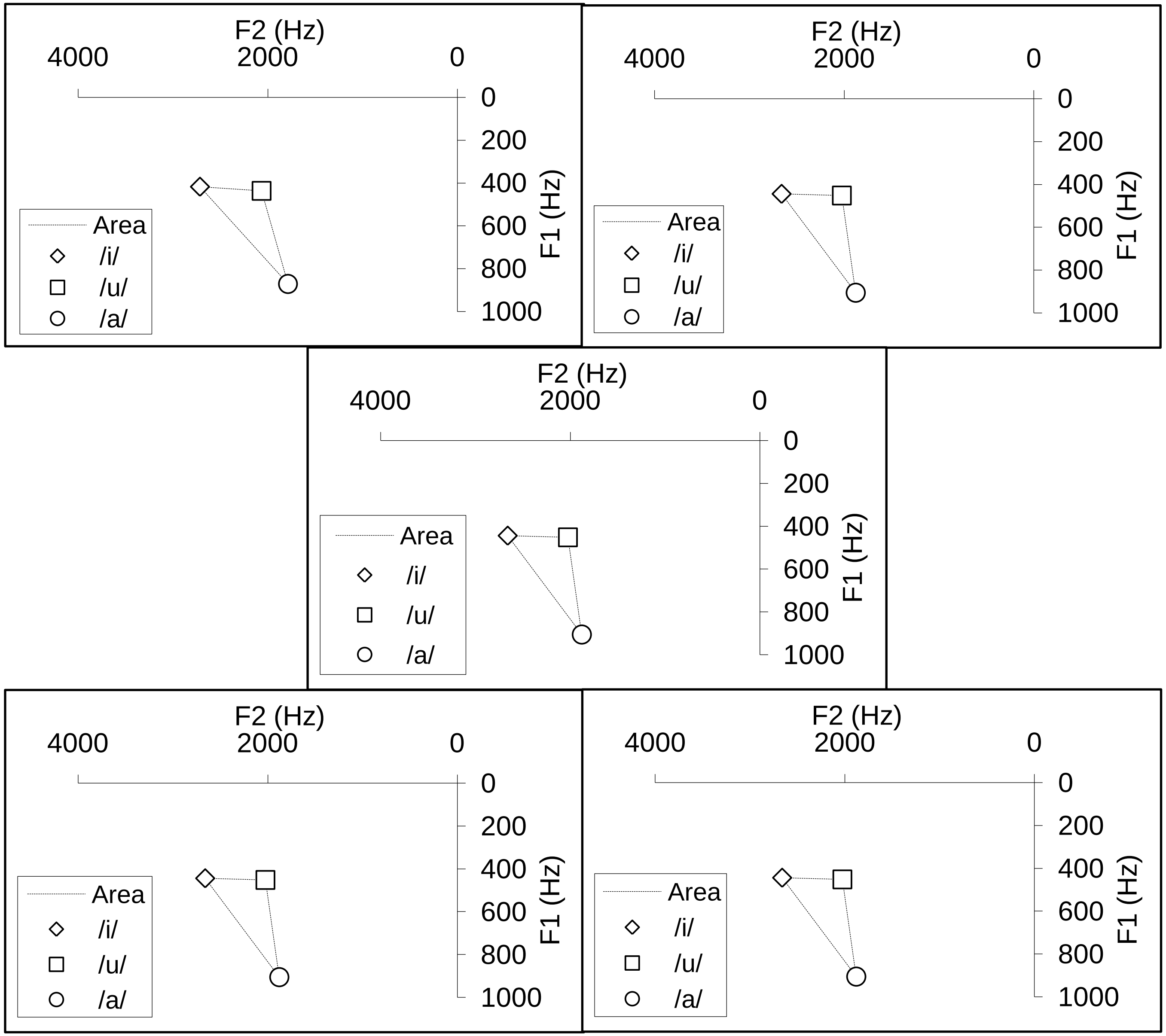

Figure 4: Vowel space diagrams for the female participants at the masking conditions of Quiet (middle), Broadband masking at 50 dB HL (top left) and 70 dB HL (top right) as well as Two-talker babble at 50 dB HL (bottom left) and 70 dB HL (bottom right).

Males

The individual results of the vowel space areas for men are shown in Table 2. The quiet condition resulted in individual vowel space areas ranging from 17321 Hz^2 to 125287 Hz^2 with a group average of 68649 Hz^2.For the broadband noise conditions, individual vowel space areas for BBN50 ranged from 29485 Hz^2 to 144103 Hz^2 with a group average of 71511 Hz^2, while for the BBN70 condition individual results ranged from 11250 Hz^2 to 246659 Hz^2, with a group average of 71383 Hz^2. The TTB50 condition resulted in individual vowel space areas ranging from 27296 Hz^2 to 124994 Hz^2, with a group mean of 60153 Hz^2. The TTB70 condition showed an individual range of 22000 Hz^2 to 114493 Hz^2, and a group average of 57768 Hz^2.The group vowel space results for each listing conditioning are displayed in Figure 5.

Males vs. Females

To evaluate the difference in vowel space between males and females a two-way ANOVA was performed. The within-groups factor was masking type and the between-groups factor was sex. There was no interaction between sex and masking [$F(4,190) = 0.359$, $p = 0.837$]. The main effect for masking type was non-significant [$F(4,190) = 0.101$, $p = 0.982$], indicating that there was no apparent Lombard Effect for vowel space. The main effect for sex was significant [$F(1, 190) = 127.980$, $p = 0.0001$]. The average vowel space for females was more than double that of males.

Table 5: Vowel space values (in Hz²) for the male (M) participants at the masking conditions of Quiet, Broadband masking at 50 (BBN50) and 70 dB HL (BBN70) as well as Two-talker babble at 50 (TTB50) and 70 dB HL (TTB70).

	BBN50	BBN70	Quiet	TTB50	TTB70
M1	105406	101354	108275	42412	73832
M2	93725	106201	17321	86560	66040
M3	55837	102751	125287	93883	54021
M4	57191	35366	82536	50988	45302
M5	99594	61661	91840	111073	85764
M6	46648	48999	48597	47517	43827
M7	44915	13760	36982	40211	44077
M8	29485	30067	37437	33285	42535
M9	46797	55197	41145	40273	40048
M10	130469	109180	101129	124994	73670
M11	75405	23127	36749	31787	49332
M12	53596	82924	74627	61112	43965
M13	87834	74320	97026	43439	44626
M14	36616	24267	53875	27296	60077
M15	144103	246659	115022	105365	114493
M16	114699	99677	98085	87295	74761
M17	70440	69872	18256	45036	44972
M18	60450	98360	107469	42931	92813
M19	46227	32663	62903	49732	39214
M20	30788	11250	18417	37867	22000
Mean	71511	71383	68649	60153	57768
SD	33589	53194	35563	29719	22269

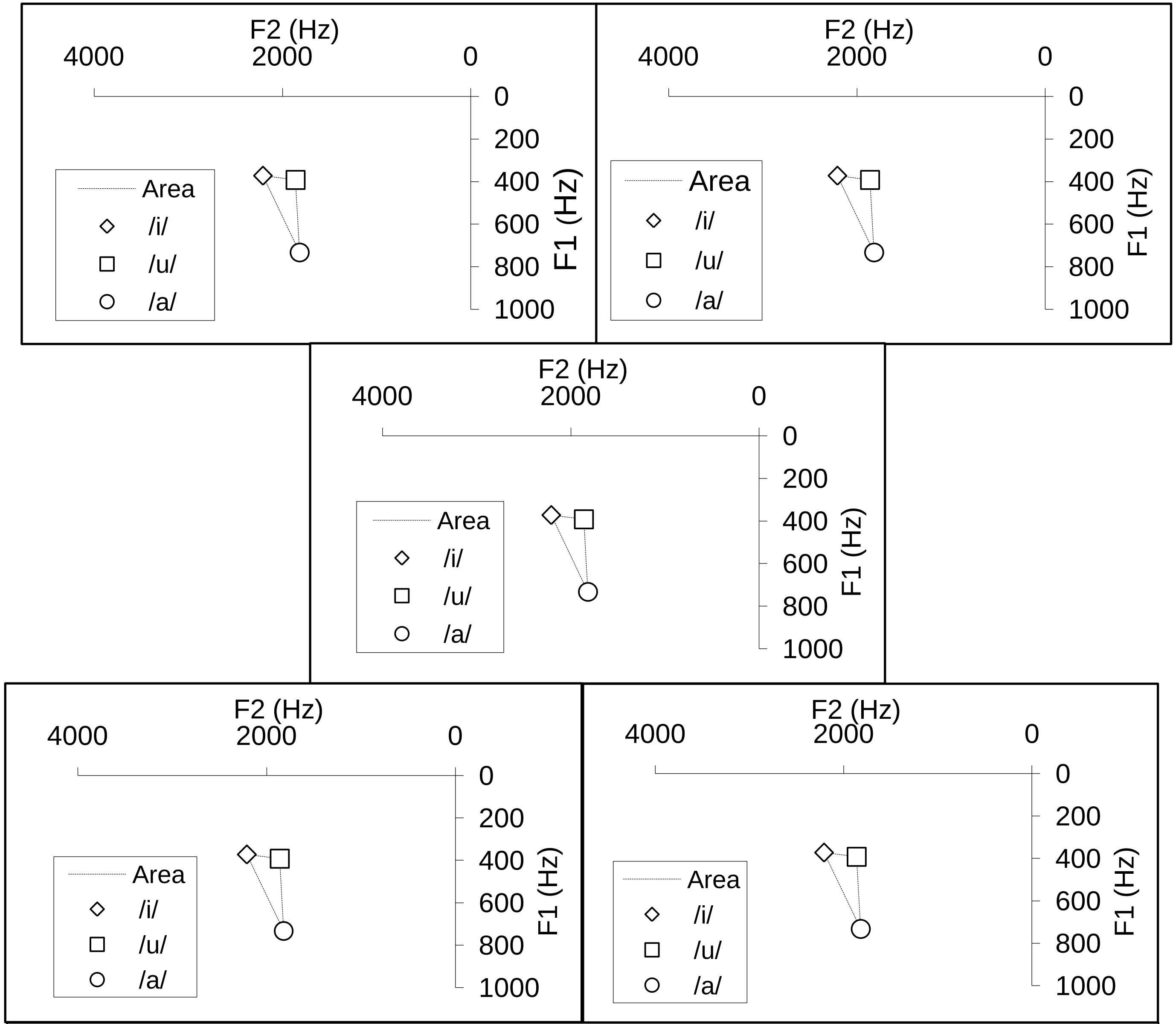

Figure 5: Vowel space diagrams for the male participants at the masking conditions of Quiet (middle), Broadband masking at 50 dB HL (top left) and 70 dB HL (top right) as well as Two-talker babble at 50 dB HL (bottom left) and 70 dB HL (bottom right).

Summary of Results

- F0 shows a significant main effect with the intensity of the noise masker and with sex. The lowest F0 was found in the quiet condition and the highest F0 was found in the two loudest masking conditions (BBN70 & TTB70).
- F0 did not show a significant main effect with the type of noise masker (e.g. broadband noise vs. two-talker babble).
- There was no significant difference found between broadband noise and two-talker babble for vowel space.
- A sex difference was found in vowel space with female's vowel space being significantly larger than males across each of the listening conditions.

Discussion

The purpose of the present study was to examine the LE at varying intensity levels of broadband noise and two-talker babble. Selected acoustic features of vowels produced by males and females were measured to determine whether the LE varied according to sex and masker type. Four research questions were posed and the discussion pertaining to each of these questions is presented below.

Research Question 1: Is there a significant sex difference in F0 in speech produced in quiet, in the presence of two-talker babble at varying intensity levels, and in the presence of broadband noise at varying intensity levels?

In the present study a significant sex difference was found for F0 during each of the listening conditions. The average F0 for females ranged from 204 Hz (in the quiet condition) to 224 Hz (in the BBN70 condition). The average F0 for males ranged from 129 Hz (in the quiet condition) to 171 Hz (in the BBN70 condition). The finding of a sex difference is not surprising given well known differences in laryngeal anatomy between women and men. In particular, the length of the vocal folds is greater in adult males (17 – 21 mm) than adult females (11 – 15 mm), and this difference will directly affect the mode of vocal fold vibration (Boone, McFarlane, Von Berg, & Zraick, 2010).

Previous studies have also investigated a sex effect on F0 in the presence of masking noise. Junqua (1993) investigated acoustic sex differences in speech produced in the presence of white-Gaussian noise and found F0 increased in the noise condition for male speakers but no such change was found for female speakers. The lack of a similar increase in F0 for female speakers was thought to be due to a ceiling effect, whereby females voices are already more high-pitched than males. In addition to measures of F0, the researchers also measured spectral energy and found considerable interspeaker variability. Among female speakers energy increased in certain bands and this trend was less apparent for the male speakers, suggesting females tend to increase vocal effort more so than males in the presence of masking noise.

Patel and Schell (2008) also examined the influence of masking noise on F0 between male and female speakers using an interactive computer game. The game required the speaker to perform a series of vocal instructions. No sex difference was found in the F0 patterns during the vocal tasks. For both male and female speakers, F0 increased as a function of two-talker noise level. This suggests that both sexes were affected equally by background noise when communicating naturally as opposed to reading. Similar to Patel and Schell, the present F0 results would indicate that both males and females increase F0 as a function of masker intensity level. While there was a significant difference in F0 for sex, there was no significant interaction between masker and sex suggesting both sexes were affected similarly by masker background.

Based on the results of the present study, it seems unlikely there was a sociophonetic influence on the between females and males. Recall, past research has suggested that females tend to use more carefully articulated speech than males particularly in experimental settings (Cheshire, 2002). In the present study, a sociophonetic influence would have presumably resulted in a pattern of F0 unique to females. However, both females and males were shown to increase their F0 in response to increases in masker intensity level. Therefore, it appears that sex differences in F0 associated with the LE are of a physiological nature. The differences in vocal fold width and thickness predetermine a baseline F0 which then increases as a function of masking noise intensity (Borden et al., 1994).

Research Question 2: Is there a significant difference in F0 in speech produced in quiet, in the presence of two-talker babble at varying intensity levels, and in the presence of broadband noise at varying intensity levels?

There was no significant difference in F0 between broadband noise and two-talker babble when the data were collapsed across males and females. However, a significant difference was found in F0 as a function of intensity level, reflecting a LE. The lowest F0 was associated with the quiet listening condition and the highest F0 was found for the highest masker intensity (BBN70 & TTB70). Possible reasons for the present findings are offered below.

The present findings agree with past research observing an increase in F0 according to masker intensity level (Summers et al., 1988; Patel & Schell, 2008). For example, Summers et al. (1988) carried out an acoustic analysis on read speech produced in broadband noise (energetic masking) and found F0 increased between quiet and the first presentation of noise (80 dB SPL) but lesser changes were noticed across more intense masking. An LE for F0 was also noticed by Patel and Schell (2008). This study examined the effect of linguistic content on Lombard speech produced in two-talker noise. Pairs playing an interactive computer game increased F0 as a function of increasing noise level, however at higher noise levels, F0 also increased as a function of word type, with the F0 of agent words (e.g. name of the dog in the interactive computer game) tending to increase the most.

In the present study, no differences in F0 were found according to masker type. The original hypothesis was that two-talker babble may contribute to linguistic interference in speech production. Accordingly, speakers may adjust their F0 differently compared to the broadband noise condition. Cooke and Lu (2010) compared the effects of different masking backgrounds on speech production alone and in pairs. These researchers concluded that both alone and in pairs, the biggest increase in F0 occurred with speech-shaped noise, while speech-modulated noise, and competing speech produced comparable but smaller changes to mean F0. The difference between the present study and Cooke and Lu may be due to differences in methodology or possibly that a LE is not dependent on masker type but simply on intensity. The methodology of the present study differs from that of Cooke and Lu (2010) in a number of ways. Both used some form of noise featuring energy across a frequency band (broadband vs. speech-modulated and speech-shaped noise) and masking with a linguistic content (two-talker babble vs. competing speech). However, the competing speech used by Cooke and Lu (2010) had more of an informational "element" to it as it was the voice of fellow participants (of the same sex) and resembled that of the target phrases. Another apparent difference in the methodology was the use of oral reading samples in the present study vs. natural conversational speech in Cooke and Lu (2010). It has been suggested in Cooke and Lu (2010) and Patel and Schell (2008) that oral reading may cause the speaker to forget the presence of masking whereas in conversational speech, the speaker is motivated to speak so as to be understood.

It is important to note however that a significant difference was found between intensity levels, therefore, the fact that the same difference was not found in F0 regardless of masking conditions would suggest that the type of masker does not have an impact on speech production. That is, a LE is not determined by masker type but is due to intensity level.

Research Question 3: Is there a significant sex difference in vowel space in speech produced in quiet, in the presence of two-talker babble at varying intensity levels, and in the presence of broadband noise at varying intensity levels?

A clear sex difference in vowel space was observed between women and men across listening conditions. The average vowel space for females ranged from 138825 Hz^2 (in quiet) to 145862 Hz² (in the TTB70 condition), while the average vowel space for males ranged from 57768 Hz² (in the TTB70 condition) to 71511 Hz² (in the BBN50 condition). This shows that the average vowel space for females was more than double that of males.

Previous studies seem to have also found a sex difference in changes to production of formant frequencies. Junqua (1993) investigated sex difference in speakers communicating in the presence of white-Gaussian noise. It was found that both males and females showed an increase in F1 frequency for many sounds (including vowels) but this was more evident in females. A similar trend was also found for females for F2 frequency. Hazan and Baker (2011) carried out an experiment where the listener's speech was acoustically analysed when the speaker was under difficult listening situations. In this case, no sex difference was found for F1, however females had a larger F2 range compared to males. For both sexes, there was a greater difference in F1 range between oral reading than conversational speech.

Two possibilities are offered as to why the vowel space area was larger in females compared to males. First, it is important to note that a sex difference was also found for F0. Therefore it is possible that basic sex differences in vocal tract anatomy are responsible for both a high F0 and large vowel space in females. Previous studies have reported that females have a larger vowel space than males (Simpson, 2009). However a recent study by Weirich and Simpson (2013) directly examined the relationship between F0 and vowel space in males and females. These researchers found females to have a larger vowel space than males, as well as higher F0, but F0 and vowel space size were not significantly correlated. This suggests that other factors must be involved which could include other biophysical factors or sociophonetics. The present results would appear to align nicely with the results of Weirich and Simpson and suggest that females may have altered their vocal tract vowel space in a unique fashion as a result of a LE.

Research Question 4: Is there a significant difference in vowel space in speech produced in quiet, in the presence of two-talker babble at varying intensity levels, and in the presence of broadband noise at varying intensity levels?

In the present study, vowel space was recorded and acoustically measured in a quiet condition, under 50 dB HL and 70 dB HL of broadband noise (BBN50 & BBN70 respectively), and under 50 dB HL and 70 dB HL of two-talker babble (TTB50 & TTB70). Based on analysis of overall vowel space, no significant difference was found for vowel space between quiet, broadband noise, and two-talker babble masking conditions. These results were taken to indicate no LE for vowel space according to masking condition.

Previous studies have reported mixed results regarding the influence of background noise type on vowel space. Cooke and Lu (2010) studied the effect of differing masking noise on speech production solving a Sudoku puzzle alone, and in pairs. This was done under the masking conditions of quiet, competing speech, speech-shaped noise, and speech-modulated noise. Analysis of vowel space for each noise condition indicated a larger vowel dispersion in quiet and speech-modulated noise, while only speech-shaped noise differed from the quiet condition when solving the puzzle alone. The researchers also examined vowel “compactness” and found that the three noise backgrounds led to tighter clustering of the exemplars for each vowel category, with the largest fall in the speech-shaped noise condition. This shows a mixed effect of noise background on vowel dispersion.

Other studies have investigated the changes in formant frequencies when speech is produced in noise. Summers et al. (1988) found that in a study of two participants using broadband noise, one increased their F1 frequency in the presence of increasing noise but F2 frequency remained relatively the same. Neither F1 nor F2 frequency changed significantly for the other participant.

In the present study, it was hypothesised that a larger vowel space would be found for the two-talker babble conditions (TTB50 & TTB70) because of possible linguistic interference. This interference would require the participants to produce vowels with greater precision, as reflected in a larger vowel space area compared to the other listening conditions. The lack of difference in vowel space area across the conditions may be due to methodological differences including the use of reading target phrases rather than producing spontaneous speech, and the use of two-talker babble rather than a masker with more informational content. It is important to recognise however, that F0 changed as a function of intensity suggesting that LE influences laryngeal aspects of speech production. The lack of change in vowel space as a function of intensity would suggest that the LE does not influence the supra-laryngeal aspect of speech production. In other words, a speaker's voice may become more tense (increase in F0) as a result of LE but the articulatory patterns of speech (e.g., tongue position, F1 & F2) are not affected.

Limitations

The present research was designed to evaluate possible acoustic changes in the speech of male and females speakers under various listening conditions. While effort was made to design a study to address four specific hypotheses, there were some aspects of the study that could have been improved. Some of the various limitations to the present study are presented below.

1. The speech samples collected for this study were based on production of CVC words in a carrier phrase. This approach was taken because it was convenient and ensured all participants were producing the same speech stimuli. In spite of these precautions, no LE was found for masker type. Previous studies have also used this approach including Summers et al. (1988). However as stated in Cooke and Lu

(2010), communicating with others provides incentive for the talker to change their speech to be better understood. Talkers are not necessarily inclined to make changes in order to communicate better with themselves even with the presence of masking noise. It is also possible that use of the carrier phrase could have led to the task becoming monotonous, causing the speakers to disregard the various masking noise conditions.

2. The babble masker chosen in the study was not strictly informational. Masking noise can have both energetic and informational masking components. Brungart (2001) defines energetic masking as noise containing energy in the same temporal and critical bands so that portions of one or both signals are inaudible. On the other hand, informational masking is a high-level masking which occurs when both the target signal and masker are audible but the listener is unable to separate the elements of the target as the masker sounds so similar (Brungart, 2001). As noted in Brungart (2001) and Brungart et al. (2001), informational masking is most detrimental when it is qualitatively similar to the target stimuli. For the present study, no measures of the quantity of energetic vs. informational masking was carried out and so it is uncertain whether any masking was provided by the noise, or whether the masking that was introduced was mostly informational or energetic. For the present study, two-speaker babble (1 male voice, 1 female voice) was used as a form of informational masker. However, it is likely there was an influence of energetic masking evident in the masker. There were many qualitative differences in these maskers voices, for example, accent, pitch, and phrase content, even of the same-sex masker. Consequently, the informational content of the masker may have been minimised. The masking designed for the present study was chosen as it was convenient and provided

linguistic content that may have influenced a LE. Still, it is possible that a LE affect may have been discovered had a different masker been chosen.

3. It is possible that the age of the participants recruited for this study may have affected the results. The participants used for this study were quite young (*M* = 25-years). The selection of these participants was based on convenience sampling because this age-group was easily accessible to the researcher. It is possible however that an older population may be more affected by the LE and may therefore show a stronger influence of the different noise backgrounds.

4. The acoustic analysis undertaken in the present study was confined to measures of F0, F1, and F2 to examine features of voice pitch and vowel space, respectively. These measures were chosen because of a specific interest in noting whether there were simple changes in pitch and vocal tract resonance associated with the LE. It is possible that collection of other acoustic measures may have shown a stronger LE as a function of background noise. Previous studies (Cooke & Lu, 2010; Hazan & Baker, 2011; Lu & Cooke, 2008; Lu & Cooke, 2009; Summers et al., 1988) have also included measures such as energy (or amplitude), spectral tilt, spectral centre of gravity, and sentence, or vowel, duration.

Directions for Future Research

A great deal of research has been carried out to better understand the perceptual and productive influences of the LE. However there remain a variety of areas to be explored concerning this unique phenomenon. One direction for future research is to examine a wider range of acoustic measures, including VOT, and to examine further the affect of different types of noise. Evaluation of alternative acoustic features may serve to discover the changes speech undergoes in noise. This could have benefits for speech, voice and hearing treatment, as well as targeting researching for how to overcome the effects of different types of noise (for example, for hearing instruments or for the situations air traffic control officers face as mentioned in Summers et al. (1988).

Research could also be directed towards people with sensori-neural hearing loss (SNHL) and the effect of noise on their speech and on their perception of speech. As noted in the limitations of this study, a sample of young adults were recruited for participation. This population also had hearing within a normal range and so future research could investigate the effect of an older population, as well as participants with various configurations of hearing loss.

There is a body of research showing that the speech of individuals with Parkinson’s disease can be improved dramatically by increasing vocal effort (Ramig, Sapir, Countryman, Pawlas, O'Brien, Hoehn, & Thompson, 2001). A treatment technique known as the Lee Silverman Voice Technique (LSVT) involves participants to model a clinician in the use of loud and exaggerated speech. This increased loudness tends to improve the precision of speech articulation. It would be interesting to consider whether individuals with Parkinson’s Disease would show similar improvements in their speech articulation under conditions of LE.

Finally, the present study was designed to examine the acoustic characteristics of speech production under conditions of quiet and masking noise. No attempts were made to examine features of speech intelligibility. Past studies have shown that speech intelligibility is improved under various masking conditions (Dreher & O’Neil, 1957; Lu & Cooke, 2008; Summers et al., 1988). Therefore, it would be worthwhile to further examine the current data set with regard to listener’s perceived intelligibility of the CVC (and carrier phrase) production as a function of sex and masker type.

Summary and Conclusion

The purpose of this study was to examine acoustic features of vowel production in males and females under the influence of broadband noise and two-talker babble. A total of 40 adults (20 males, 20 females) were selected and required to read phrases containing target vowels while being exposed to quiet, broadband noise at intensities of 50 and 70 dB HL, and two-talker babble at intensities of 50 and 70 dB HL. The results indicated that there was no effect of masker type on F0, but the intensity of the masker showed a LE on F0. A sex difference was also found for F0. From the results of this study and past research it can be concluded that there is a LE for F0 with intensity level but not as a function of masker type. There was no apparent LE for vowel space across different masker conditions, although females were found to have a larger vowel space compared to males across all conditions. The combined results for F0 and vowel space would suggest there is a LE for acoustic features of speech produced at the laryngeal level (i.e. increasing F0) but no such effect is evident for supra-laryngeal articulation (i.e. no change in vowel space). There may also be a sociophonetic influence regarding vowel space articulation with females exhibiting a significantly larger vowel space compared to males.

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Appendix 1

Human Ethics Committee Approval Letter.

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

HUMAN ETHICS COMMITTEE

Secretary, Lynda Griffioen
Email: human-ethics@canterbury.ac.nz

Ref: HEC 2013/54

10 June 2013

Victoria Askin
Department of Communication Disorders
UNIVERSITY OF CANTERBURY

Dear Victoria

The Human Ethics Committee advises that your research proposal "Effects of masking, and sex on Lombard vowel production" has been considered and approved.

Please note that this approval is subject to the incorporation of the amendments you have provided in your email of 6 June 2013.

Best wishes for your project.

Yours sincerely

Lindsey MacDonald
Chair
University of Canterbury Human Ethics Committee

Appendix 2

Information sheet for participants, Consent form for participants.

Department of Communication Disorders

Information for Participants

You are invited to participate in the research project entitled *Effects of Masking, and Sex on Lombard Vowel Production.*

The aim of this project is to evaluate the effects of different types of background noise on your speaking behaviour. As part of this project you will be asked to read aloud while listening to various types of background noise. Your speech will be audio recorded during these speaking tasks and will be later analysed acoustically. We are interested in determining whether speaking while listening to informational masking (two-talker babble) differs from energetic masking (white-noise) in terms of vowel production, and whether this effect is different depending on the sex of the speaker.

Your involvement in this project will involve one session, lasting approximately 1 hour. This session will include a hearing test to ensure normal hearing. In the event that you are found to have hearing levels that fall outside the normal hearing range, a follow up referral to the University of Canterbury Speech and Hearing Clinic will be made. After completion of the hearing screen you will then be required to read various carrier phrases while wearing headphones. Each phrase will contain a set of consonants and a vowel (CVC), such as "BAT", and you will be asked to produce this a number of times using a variety of different CVC combinations. Background noise will be presented to your ears through the headphones while you are reading these phrases.

The results of the study may be published, and the Master's Thesis is a public document via the University of Canterbury Library Database, but you may be assured of the complete confidentiality of the data gathered in this investigation. The identity of participants will not be made public. To ensure confidentiality, the information gathered will be assigned a number and all identifiable information will be removed. Data will be kept in a locked filing cabinet within a lockable room in the Department of Communication Disorders at the University of Canterbury. You have the right to withdraw from participating in this study at any time, including during testing, up until the data have been incorporated into the overall group findings. The data will be held securely for 5 years after publication in a refereed journal. After this period, all data will be destroyed.

The project is being carried out as a requirement for a Masters of Audiology by Victoria Askin under the supervision of Professor Michael Robb. The project has been reviewed ***and approved*** by the University of Canterbury Human Ethics Committee. If you have any further questions about the research project, please do not hesitate to contact either my supervisor or myself at the University of Canterbury. Thank you once again.

Sincerely,

Victoria Askin BSLT
Master of Audiology Student
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Professor Michael Robb
Dept of Communication Disorders
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Effects of Masking, and Sex on Lombard Vowel Production

UNIVERSITY OF CANTERBURY
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CHRISTCHURCH NEW ZEALAND

Consent Form

____
Name

____
Address

____
Phone number

I have been fully informed by Victoria Askin about the study mentioned above. I have received a copy of the information sheet, and I have read and understood the "Information for Participants". In addition, I was invited to discuss the project, and all my questions have been answered accordingly.

I have had sufficient time to decide whether I would like to participate in the study, and I understand that participation is voluntary. I have been informed that I may withdraw from the study, including withdrawal of any information I have provided, and that I do not have to give a reason. Withdrawal from this study will only be possible up until the data have been incorporated into the overall group findings.

I note that the project has been reviewed and approved by the University of Canterbury Human Ethics Committee. I understand that all my data will be saved and stored anonymously, and that it will exclusively be used for scientific purposes.

I agree to voluntarily participate in the study, and I consent to publication of the results of the study with the understanding that anonymity will be preserved.

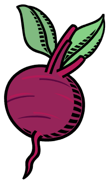
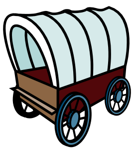
____
Place, Date Signed (participant)

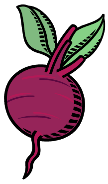
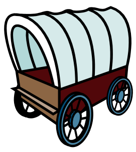
____
Place, Date Signed (researcher)

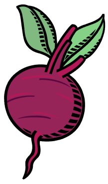
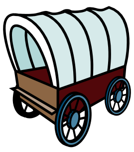
Department of Communication Disorders, University of Canterbury
, Christchurch 8020, New Zealand.
Tel: +64 3 364-2987 x7077, Fax: +64 3 364 2260
www.cmds.canterbury.ac.nz

Appendix 3

Picture and phrase stimuli.

say **Beet** again 	say **Pete** again 	say **Deet** again 
say **Teet** again 	say **Keet** again 	say **Geet** again
say **Boot** again 	say **Poot** again	say **Doot** again 
say **Toot** again 	say **Koot** again 	say **Goot** again 
say **Bart** again 	say **Part** again 	say **Dart** again 
say **Tart** again 	say **Cart** again 	say **Gart** again 

I put a **Beet** in there 	I put a **Pete** in there 	I put a **Deet** in there 
I put a **Teet** in there 	I put a **Keet** in there 	I put a **Geet** in there
I put a **Boot** in there 	I put a **Poot** in there	I put a **Doot** in there 
I put a **Toot** in there 	I put a **Koot** in there 	I put a **Goot** in there 
I put a **Bart** in there 	I put a **Part** in there 	I put a **Dart** in there 
I put a **Tart** in there 	I put a **Cart** in there 	I put a **Gart** in there 

I saw a **Beet** today 	I saw a **Pete** today 	I saw a **Deet** today 
I saw a **Teet** today 	I saw a **Keet** today 	I saw a **Geet** today
I saw a **Boot** today 	I saw a **Poot** today	I saw a **Doot** today 
I saw a **Toot** today 	I saw a **Koot** today 	I saw a **Goot** today 
I saw a **Bart** today 	I saw a **Part** today 	I saw a **Dart** today 
I saw a **Tart** today 	I saw a **Cart** today 	I saw a **Gart** today 

Appendix 4

The Rainbow Passage (Fairbanks, 1960).

When the sunlight strikes raindrops in the air, they act as a prism and form a rainbow. The rainbow is a division of white light into many beautiful colours. These take the shape of a long round arch, with its path high above, and its two ends apparently beyond the horizon. There is, according to legend, a boiling pot of gold at one end. People look, but no one ever finds it. When a man looks for something beyond his reach, his friends say he is looking for the pot of gold at the end of the rainbow.

Appendix 5:

Fundamental frequency (FO), First Formant (F1) and Second Formant (F2) frequency values

(in Hz) for females (F) across vowel and noise condition.

	BBN50								
	/a/			/i/			/u/		
	F0	F1	F2	F0	F1	F2	F0	F1	F2
F1	138.1	865.9	2430.0	181.9	366.9	2817.6	189.1	359.5	2483.8
F2	-	933.9	1835.4	221.9	379.8	2607.5	226.2	389.8	1893.9
F3	233.1	1059.6	1760.8	246.4	453.6	2839.0	232.1	448.8	2012.8
F4	196.4	854.4	1676.7	213.5	443.4	2711.1	213.4	494.2	2091.1
F5	180.5	952.4	1666.6	187.4	406.4	2696.0	203.0	418.7	1917.1
F6	204.7	704.3	1270.1	224.1	443.8	2603.3	219.8	439.4	1969.3
F7	209.1	863.2	1880.2	212.9	401.1	2943.1	228.3	417.2	2458.3
F8	213.5	710.4	2384.8	226.0	446.6	2670.2	212.4	449.7	2204.1
F9	208.8	880.1	1623.9	215.0	441.4	2750.8	222.9	450.4	1842.0
F10	224.0	806.7	1634.3	242.7	388.8	2747.3	239.4	515.5	1727.4
F11	197.4	859.5	1709.2	214.2	433.7	2844.9	219.2	433.3	2152.8
F12	204.6	834.8	1628.3	215.1	345.4	2586.2	218.5	355.5	1829.9
F13	221.1	962.4	1874.5	243.6	460.4	2705.5	-	483.1	2051.6
F14	173.2	908.2	1612.1	191.1	479.3	2488.2	189.0	482.9	2023.7
F15	222.5	860.3	1773.0	223.0	483.9	2650.6	235.2	487.7	2173.7
F16	227.3	898.2	1685.8	-	379.1	2572.5	234.0	402.1	1855.8
F17	202.5	935.0	1958.4	215.7	431.3	2995.2	212.4	463.3	2365.2
F18	202.9	836.5	1490.4	223.4	420.7	2676.4	221.7	428.4	2041.4
F19	241.8	885.4	1989.7	188.5	354.0	2834.1	236.8	393.7	2178.5
F20	186.0	808.3	1841.8	201.3	396.6	2512.6	198.3	413.3	2020.7
Mean	204.6	871.1	1786.3	215.1	417.8	2712.6	218.5	436.3	2064.7
SD	23.9	79.3	261.5	18.7	40.4	136.0	15.2	44.1	205.6

	BBN70								
	/a/			/i/			/u/		
	F0	F1	F2	F0	F1	F2	F0	F1	F2
F1	209.3	910.3	2407.4	236.9	370.0	2776.3	225.4	361.4	2428.9
F2	229.7	829.9	1509.1	238.1	467.3	2353.1	227.3	485.0	1804.9
F3	198.6	1009.9	1583.9	-	444.9	2785.9	223.9	468.4	2017.6
F4	233.3	931.5	1654.3	236.6	468.7	2672.7	236.2	483.7	1991.4
F5	194.1	930.5	1749.2	215.2	436.3	2657.6	212.1	415.9	2030.3
F6	209.3	710.1	1268.5	234.0	459.3	2612.7	220.9	446.8	1831.4
F7	247.8	909.6	1797.1	210.0	477.3	2838.1	235.8	500.4	2328.5
F8	214.9	794.2	1949.9	224.4	422.3	2635.7	217.4	436.1	2089.5
F9	159.7	812.6	1786.3	193.1	420.8	2697.6	209.0	435.5	1908.1
F10	216.1	828.5	1858.1	233.9	386.2	2607.7	234.1	418.8	1767.1
F11	214.5	935.2	1987.7	230.9	450.4	2836.9	236.2	460.1	2265.1
F12	-	915.6	1809.6	-	365.3	2664.0	213.0	379.8	1777.8
F13	244.6	976.7	1663.8	-	523.3	2542.2	246.4	524.6	2035.4
F14	195.6	920.0	1654.8	196.7	490.2	2557.3	210.0	464.1	2068.6
F15	244.4	927.8	1864.3	-	515.4	2642.3	-	579.1	1934.0
F16	232.8	910.1	1730.2	221.6	370.6	2534.7	194.3	419.9	1830.3
F17	220.7	979.0	2270.8	241.7	628.5	2762.5	246.4	598.3	2123.0
F18	232.6	947.2	1652.5	229.9	458.8	2648.7	238.5	448.3	2027.2
F19	218.7	948.3	2004.7	226.0	417.3	2686.2	225.7	438.4	2117.6
F20	238.1	847.5	1574.9	247.1	395.9	2529.0	235.8	344.7	1991.2
Mean	218.7	898.7	1788.9	226.0	448.4	2652.1	225.7	455.5	2018.4
SD	21.8	71.2	250.0	15.4	62.6	117.3	13.9	63.5	179.5

	Quiet								
	/a/			/i/			/u/		
	F0	F1	F2	F0	F1	F2	F0	F1	F2
F1	135.7	872.4	2618.2	149.4	350.6	2882.6	159.5	343.6	2504.8
F2	226.0	827.6	1758.5	167.9	430.3	2612.1	239.4	429.7	1842.6
F3	145.1	1054.3	1855.9	196.8	414.9	2821.7	199.4	406.6	2086.8
F4	197.0	608.2	2204.1	197.4	505.3	2386.7	192.6	552.8	2057.3
F5	219.4	933.4	1760.1	219.4	400.3	2668.8	207.6	406.8	2134.5
F6	195.8	688.9	1668.6	209.3	412.9	2573.4	205.9	411.8	2043.3
F7	202.4	862.1	1885.7	216.6	402.0	2981.5	212.8	412.8	2342.0
F8	221.4	692.2	2263.5	227.4	437.9	2778.5	222.2	448.9	2295.3
F9	206.1	844.7	1612.1	205.0	412.4	2951.2	234.4	438.1	1965.9
F10	226.1	806.4	2003.2	239.2	350.4	2750.2	236.2	376.8	1684.1
F11	191.4	926.1	2178.8	216.6	414.2	2795.7	205.5	405.5	2290.0
F12	241.4	849.8	1534.7	-	332.8	2741.9	-	342.4	1921.9
F13	147.5	928.9	1688.9	216.2	415.9	2666.3	-	439.7	1676.5
F14	169.9	941.2	1782.1	182.1	457.3	2522.1	188.4	438.5	2020.7
F15	186.4	797.1	1809.6	206.9	444.4	2663.6	216.0	494.5	1940.1
F16	208.5	811.7	1593.1	232.4	423.8	2542.6	230.9	440.6	1912.8
F17	206.6	896.0	2585.2	214.0	428.4	3063.8	216.8	452.2	2489.2
F18	178.3	812.0	1795.3	217.5	433.3	2760.9	215.1	437.1	2091.5
F19	196.7	858.1	1835.3	203.5	391.8	2771.2	214.5	389.7	2062.0
F20	177.9	794.1	1882.5	205.0	399.1	2531.9	205.0	399.1	2531.9
Mean	194.0	840.3	1915.8	206.5	412.9	2723.3	211.2	423.4	2094.7
SD	28.5	97.6	298.4	21.6	38.6	170.2	19.3	47.3	248.9

	TTB50								
	/a/			/i/			/u/		
	F0	F1	F2	F0	F1	F2	F0	F1	F2
F1	126.3	857.0	2534.8	174.6	347.7	2831.7	166.4	346.1	2518.3
F2	207.4	832.5	2043.3	224.7	456.0	2393.7	225.5	463.4	1836.8
F3	-	1081.3	1708.9	222.2	446.6	2783.5	197.0	415.4	2026.7
F4	196.0	851.3	1854.3	209.4	443.9	2675.1	211.0	475.0	2111.8
F5	188.9	907.0	1654.6	206.0	405.0	2730.0	217.5	411.0	2086.6
F6	195.2	673.1	1424.2	215.8	423.5	2580.6	206.7	435.1	1946.2
F7	205.4	854.7	1881.0	217.8	426.4	2847.1	225.2	418.5	2564.2
F8	206.7	771.0	2013.1	222.7	403.9	2705.9	218.1	425.6	2117.0
F9	202.45	874.6	1629.4	227.5	434.4	2859.1	216.8	460.5	1918.5
F10	206.6	833.8	1567.1	231.3	415.9	2659.9	219.2	408.2	1761.7
F11	208.4	841.6	1663.5	223.0	392.9	2857.8	227.9	428.6	2110.5
F12	239.4	853.8	1469.1	-	348.9	2681.5	149.5	349.0	1721.5
F13	227.3	1010.9	1979.4	-	448.2	2654.3	235.2	464.2	1958.5
F14	176.3	898.7	1782.8	184.4	429.1	2575.2	194.1	485.4	2018.2
F15	224.2	846.1	2099.4	240.4	472.3	2682.3	236.6	466.8	2360.0
F16	222.3	891.4	1644.1	237.5	374.9	2594.9	228.3	371.4	1850.6
F17	186.1	907.3	2014.5	204.7	431.2	2990.8	208.8	448.3	2142.7
F18	209.6	818.8	1900.2	222.8	428.3	2721.2	226.4	427.8	2057.3
F19	236.3	872.7	2107.9	202.9	395.9	2817.4	-	404.3	2213.7
F20	213.5	799.5	1610.2	229.3	456.3	2578.1	230.2	451.8	2166.8
Mean	204.1	863.9	1829.1	216.5	419.1	2711.0	212.7	427.8	2074.4
SD	25.0	80.3	260.1	17.2	34.1	135.3	22.7	39.3	223.0

	TTB70								
	/a/			/i/			/u/		
	F0	F1	F2	F0	F1	F2	F0	F1	F2
F1	176.4	888.9	2599.2	220.2	377.7	2735.6	197.0	350.5	2368.7
F2	223.4	863.3	2348.8	236.6	440.9	2443.2	233.8	465.2	1805.9
F3	211.8	952.8	1586.3	-	457.9	2837.6	235.2	459.0	1987.1
F4	211.6	878.4	1697.5	227.5	448.9	2643.8	230.3	469.5	2003.9
F5	211.8	907.8	1632.8	221.5	436.6	2714.2	216.6	420.8	2078.1
F6	200.3	692.1	1457.1	212.1	426.2	2599.6	216.2	438.4	1981.8
F7	234.9	888.1	1773.0	189.1	446.7	2836.2	241.9	464.5	2213.7
F8	236.9	807.8	1907.9	246.4	438.6	2591.5	222.5	435.0	2044.7
F9	201.0	865.4	1762.2	201.4	463.1	2685.2	225.8	474.4	1914.4
F10	230.5	1124.6	2782.4	236.7	414.9	2696.9	245.0	410.6	1742.3
F11	205.3	831.4	1799.1	221.5	474.2	2789.3	233.4	478.5	2308.7
F12	216.4	900.6	1664.3	225.3	367.1	2732.0	226.6	377.7	1836.6
F13	-	1024.8	2094.3	-	490.7	2583.2	227.3	507.2	1935.4
F14	192.9	962.4	1795.8	204.9	506.5	2558.7	207.3	507.8	2049.0
F15	231.5	906.5	1976.7	241.2	485.0	2602.2	235.3	499.2	2026.2
F16	229.5	973.5	1770.7	240.6	383.3	2589.3	-	397.7	1862.6
F17	236.1	994.7	1824.7	236.2	537.0	2785.5	243.7	573.3	2118.8
F18	221.6	890.9	1642.3	229.3	490.2	2628.5	228.2	500.3	2009.3
F19	216.4	960.9	1875.8	225.3	410.8	2617.8	226.6	414.8	2105.1
F20	223.8	795.4	1561.0	239.6	400.2	2489.6	212.9	396.1	2105.2
Mean	216.4	905.5	1877.6	225.3	444.8	2658.0	226.6	452.0	2024.9
SD	16.2	89.7	333.6	15.5	44.9	108.3	12.5	53.2	157.9

Appendix 6

Fundamental frequency (FO), First Formant (F1) and Second Formant (F2) frequency values (in Hz) for males (M) across vowel and noise condition.

	BBN50								
	/a/			/i/			/u/		
	F0	F1	F2	F0	F1	F2	F0	F1	F2
M1	134.6	759.8	1241.0	148.9	429.9	2236.8	145.0	356.5	1819.2
M2	142.7	609.8	1163.9	157.3	310.0	2350.4	162.8	322.2	1676.9
M3	116.3	693.2	1315.9	140.2	340.3	2468.0	142.1	382.1	2015.1
M4	170.3	631.9	1309.0	179.4	365.1	1939.1	183.6	372.7	1492.4
M5	133.6	753.6	1365.3	146.3	318.7	2147.5	142.1	349.5	1634.1
M6	148.1	673.1	2387.3	156.3	397.5	2194.1	151.5	406.9	1862.1
M7	138.8	725.8	1703.7	157.5	337.5	2186.0	157.6	359.7	1927.1
M8	126.9	619.2	1543.8	141.3	308.6	2118.2	145.9	303.0	1938.6
M9	149.7	685.0	2229.6	160.3	334.0	2245.4	160.8	358.9	1977.6
M10	169.8	711.5	1196.5	184.0	387.3	2229.9	180.4	381.4	1443.8
M11	124.5	712.3	1632.9	139.2	349.9	2226.3	144.1	342.9	1821.5
M12	113.1	651.2	1195.4	119.5	362.0	2061.2	118.8	360.9	1693.9
M13	119.1	775.7	1641.1	118.8	321.5	2269.1	131.5	334.5	1864.3
M14	126.5	699.0	1271.8	142.8	351.7	2302.3	137.8	384.1	1995.3
M15	139.4	699.6	1306.8	152.7	293.6	2541.1	160.2	316.3	1762.0
M16	134.4	931.7	2199.4	141.0	314.5	2337.9	140.2	321.0	1964.8
M17	123.9	595.6	1232.9	132.6	325.6	2143.2	136.0	355.6	1520.2
M18	139.8	815.1	1986.2	159.6	384.1	2205.5	154.8	412.9	1910.4
M19	159.7	707.8	1788.0	175.5	372.6	2327.8	172.3	393.0	2019.1
M20	148.9	610.7	1459.7	161.1	320.9	2087.0	165.6	358.5	1793.1
Mean	138.0	703.1	1558.5	150.7	346.3	2230.8	151.7	358.6	1806.6
SD	16.3	78.0	371.2	17.5	35.0	137.7	16.5	29.9	178.0

	BBN70								
	/a/			/i/			/u/		
	F0	F1	F2	F0	F1	F2	F0	F1	F2
M1	150.6	757.2	1837.1	158.1	349.1	2288.0	160.2	353.2	1786.8
M2	148.8	640.0	1164.4	162.3	317.9	2292.7	164.3	332.0	1584.0
M3	131.1	753.5	1978.6	152.9	333.3	2564.6	155.5	369.4	2025.3
M4	226.8	714.4	2326.9	228.1	490.1	1856.1	236.7	508.5	1579.2
M5	121.0	733.3	1412.2	121.8	350.3	2114.4	132.1	394.1	1712.1
M6	159.2	693.7	2034.1	160.9	415.4	2145.6	171.3	420.4	1791.5
M7	139.4	777.4	2239.5	146.8	339.9	2096.3	152.7	407.3	2055.4
M8	153.5	681.7	1599.0	176.9	326.6	2175.9	179.6	341.3	1982.6
M9	179.6	715.8	1650.9	185.7	378.3	2151.3	186.8	386.7	1811.7
M10	200.9	759.3	1247.6	221.4	402.5	2103.3	214.7	458.7	1356.6
M11	155.6	771.1	2220.8	170.6	362.0	2091.2	172.5	378.5	1983.4
M12	129.3	705.4	2027.0	138.7	321.9	2095.8	137.1	333.6	1661.3
M13	113.2	738.2	1441.2	121.5	347.0	2293.4	122.3	386.2	1828.0
M14	171.4	730.3	2018.6	188.3	456.3	2129.5	196.6	422.2	1966.2
M15	231.7	941.1	2597.4	242.2	395.7	2534.6	239.5	564.1	1649.4
M16	141.6	936.7	2334.9	146.4	317.4	2354.6	150.9	332.9	2032.1
M17	153.2	709.6	1627.6	177.5	388.5	1950.5	183.7	404.0	1499.8
M18	191.9	857.9	1857.5	214.7	441.1	2039.8	212.1	436.5	1569.8
M19	191.1	733.0	1919.3	191.0	408.2	2158.2	179.0	371.0	1984.4
M20	158.5	631.5	1789.8	168.8	357.9	2008.4	175.9	399.0	1893.3
Mean	162.4	749.1	1866.2	173.7	375.0	2172.2	176.2	400.0	1787.6
SD	32.6	79.2	372.0	33.6	49.0	175.3	32.0	59.1	203.9

	Quiet								
	/a/			/i/			/u/		
	F0	F1	F2	F0	F1	F2	F0	F1	F2
M1	120.0	709.4	1791.1	145.9	358.1	2440.9	137.8	370.9	1801.0
M2	141.2	589.0	1200.8	152.1	302.8	2442.5	152.3	471.7	1830.7
M3	108.3	697.2	2540.4	121.1	340.1	2330.9	127.5	368.1	1645.7
M4	136.8	649.0	1496.6	151.5	356.0	2119.7	155.8	362.1	1543.4
M5	110.3	746.6	1303.3	132.7	320.9	2198.2	116.8	346.5	1712.9
M6	133.2	669.5	2061.7	141.4	393.5	2146.0	144.1	413.4	1787.7
M7	118.7	702.3	1442.5	126.7	279.2	2215.1	133.5	306.1	1991.2
M8	114.2	609.5	2447.6	121.1	302.7	2206.1	127.4	294.2	1955.4
M9	121.4	646.5	1989.3	129.0	343.5	2392.6	127.2	378.2	2074.8
M10	125.7	706.8	1401.6	127.0	385.7	2150.2	128.9	398.1	1491.2
M11	123.9	700.2	1528.6	142.7	332.5	2230.8	142.7	343.9	2009.2
M12	104.6	668.2	1395.0	110.1	315.9	2257.0	111.6	332.3	1793.2
M13	108.7	744.6	1572.2	124.4	314.0	2315.4	120.0	341.6	1817.2
M14	97.8	676.8	2530.0	105.3	366.1	2349.8	103.7	393.9	2019.1
M15	120.3	651.1	1342.0	126.8	281.9	2603.5	132.2	304.5	1903.1
M16	127.1	828.7	2067.0	130.8	308.9	2365.3	133.4	336.1	1972.3
M17	114.6	596.3	1170.2	128.1	304.1	2067.5	133.3	327.9	1869.4
M18	100.1	674.1	2073.8	110.2	357.5	2435.4	107.2	373.9	1738.0
M19	119.5	699.5	1896.3	183.6	376.1	2282.3	168.6	378.4	1890.5
M20	136.7	633.7	2057.2	157.4	321.1	2050.1	157.8	356.9	1933.1
Mean	119.2	680.0	1765.4	133.4	333.0	2280.0	133.1	359.9	1838.9
SD	12.2	54.5	429.1	18.5	33.2	142.8	17.1	41.3	156.7

	TTB50								
	/a/			/i/			/u/		
	F0	F1	F2	F0	F1	F2	F0	F1	F2
M1	136.6	762.3	1483.1	154.5	354.5	2300.5	151.7	364.3	2073.0
M2	150.5	616.0	1169.6	157.3	317.7	2340.8	159.0	329.3	1714.7
M3	134.6	731.5	1931.3	146.6	331.0	2462.3	151.8	372.8	1938.1
M4	203.0	679.5	1642.0	214.7	433.7	1918.2	207.5	427.7	1510.1
M5	118.2	739.3	1391.3	132.5	346.8	2096.7	128.6	361.2	1504.8
M6	136.2	683.0	1888.2	143.3	393.5	2119.3	144.7	421.0	1769.1
M7	151.1	743.5	2277.6	166.9	325.6	2160.3	163.5	367.0	1979.5
M8	134.9	575.6	1423.5	153.9	304.9	2193.4	146.3	309.2	1935.2
M9	132.5	669.6	1823.6	140.3	332.8	2298.0	139.7	369.3	2007.4
M10	165.6	727.1	1256.2	167.5	387.5	2188.8	167.7	416.3	1373.6
M11	120.3	716.3	1517.6	136.8	336.5	2112.2	139.0	353.4	1918.4
M12	108.6	666.0	1366.9	115.5	354.6	2183.2	113.7	368.8	1753.3
M13	126.2	785.2	1979.3	122.0	315.9	2308.5	130.3	327.1	2115.4
M14	113.7	685.0	1673.7	121.4	375.8	2219.7	123.0	410.6	1981.7
M15	137.9	690.6	1473.9	152.6	278.6	2579.1	148.2	317.1	1964.3
M16	135.8	902.2	2144.3	142.3	326.5	2288.2	142.1	316.4	1987.4
M17	123.5	619.4	1305.3	135.3	353.3	2199.6	139.3	373.5	1793.3
M18	126.6	824.6	2260.8	141.9	390.1	2162.9	139.5	412.1	1970.2
M19	154.3	694.1	1996.1	166.4	368.4	2321.4	166.7	371.6	2012.8
M20	141.8	741.4	1701.2	150.2	319.9	2211.7	158.1	357.5	1986.4
Mean	137.6	712.6	1685.3	148.1	347.4	2233.2	148.0	367.3	1864.5
SD	20.9	72.0	328.9	21.6	36.3	140.0	20.0	36.1	203.3

	TTB70								
	/a/			/i/			/u/		
	F0	F1	F2	F0	F1	F2	F0	F1	F2
M1	155.7	775.7	1906.0	166.7	345.4	2309.7	166.9	360.8	1952.0
M2	147.7	626.6	1279.0	161.4	318.2	2201.5	164.6	350.2	1677.2
M3	141.0	738.1	1993.7	158.0	353.3	2514.2	163.4	384.2	2191.6
M4	225.6	707.8	1926.6	232.3	478.9	1885.1	225.6	470.3	1487.7
M5	134.2	749.4	1302.0	153.4	354.0	2144.8	145.9	381.2	1653.0
M6	166.5	696.1	2463.0	173.3	400.4	2157.5	174.6	403.1	1863.8
M7	174.1	755.4	1934.4	199.7	380.2	2136.6	197.1	404.4	1888.6
M8	158.4	684.6	1501.5	178.2	318.1	2163.8	177.5	338.7	1894.6
M9	163.1	735.9	2220.4	169.0	351.3	2191.3	171.7	371.3	1984.5
M10	206.9	716.9	1496.8	217.6	411.7	2168.9	209.5	433.8	1637.4
M11	141.6	776.9	2301.3	158.0	393.1	2223.8	159.4	390.1	1966.2
M12	126.2	681.3	1722.5	138.2	346.4	2015.1	135.5	351.7	1747.8
M13	104.5	740.6	1478.8	111.0	375.2	2303.7	111.6	389.0	2028.3
M14	164.3	718.6	2073.6	176.1	371.1	2281.2	188.8	419.7	1906.5
M15	181.6	763.3	1555.2	201.8	439.4	2652.7	198.3	412.2	2037.8
M16	143.4	895.6	2204.7	151.4	330.9	2249.3	145.4	359.1	1982.2
M17	138.5	658.7	1653.9	148.9	373.8	2191.5	154.9	398.4	1829.3
M18	145.6	793.0	2001.7	159.3	360.2	2185.0	160.4	401.2	1738.7
M19	164.6	725.1	1828.1	184.4	393.4	2216.5	196.8	415.8	1953.9
M20	149.2	710.9	1532.8	167.0	358.7	1979.6	170.7	398.8	1803.8
Mean	156.6	732.5	1818.8	170.3	372.7	2208.6	170.9	391.7	1861.2
SD	27.0	55.0	330.6	27.6	39.5	166.8	26.8	31.6	166.8