THE EFFECTS OF NOISE AND LOW-PASS FILTERING ON THE PERCEPTION OF TONES AND CONSONANTS IN MANDARIN

by

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ABSTRACT

The purpose of the present study was to investigate how low-pass filtering and background noise affect the perception of Mandarin tones and initial consonants. Ten subjects (all native Mandarin speakers) listened to Mandarin syllables in varying conditions of background noise and filtering and were forced to guess at which consonant or tone was presented. It was found that low-pass filtering had no effect on the perception of tone, although significant main effects of background noise and tone presented were found and a significant interaction of background noise and tone was found in the perception of Mandarin tones. Low-pass filtering, background noise and tone were all found to have a significant effect on consonant perception, and significant interactions were found between background noise and filtering and between background noise and tone in the perception of Mandarin initial consonants. An investigation of the articulatory features of Mandarin consonants demonstrated that background noise and low-pass filtering have little effect on the amount of information transmitted by the features of voicing, nasality and aspiration, whereas they both have a negative effect on the amount of information transmitted by the features of manner of articulation and place of articulation.

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1. LITERATURE REVIEW

1.1 Introduction

The effects that hearing loss and background noise have on speech perception have been studied extensively in English. However, there is little information available on how they can affect the perception of a tone language, such as Mandarin.

Do both hearing loss and background noise affect consonant recognition for a tone language? Does hearing loss cause as many perceptual confusions in Mandarin as it does in a non-tonal language such as English? How do background noise and low-pass filtering affect the perception of tone? Does tone recognition offer redundancy complementary to consonant recognition such that speech perception is supported?

In this study I will attempt to answer these questions by having normal-hearing subjects listen to and recognize the consonants and tones of Mandarin, with and without the presence of competing white noise and low-pass filtering. In September, 1996, in Vancouver, British Columbia, 32.46% of all students in the public school system spoke either Mandarin or Cantonese, both 'tone' languages, as their first language, and these students represent 66.29% of all "English as a second language" students (Vancouver School Board, 1997). It is hoped that what is learned through this study may then help guide audiologists and others in providing effective aural rehabilitation and listening environments for Mandarin listeners, as well as guiding further research regarding the effects of hearing loss on the perception of tone languages.

1.2 Chapter Outline

In this chapter we will first review the effects of competing noise and filtering on speech perception. An overview of the phonology of Mandarin will then be given, followed by a description of some acoustical studies of Mandarin tones. Finally, experiments on the perception of Mandarin tones will be discussed, as well as a model of tonal perception.

1.3 Speech Perception: A Study by Miller and Nicely (1955)

1.3.1 Method

In a seminal study by Miller and Nicely (1955) entitled "An Analysis of Perceptual Confusions Among Some English Consonants", the types of perceptual errors that occur in the presence of background noise and filtering were investigated. Sixteen English consonants were presented in a range of conditions of filtering and with competing masking noise at a range of signal-to-noise ratios (S:N). The sixteen consonants were picked because the authors felt that these consonants would probably be confused most often. These consonants included all the English phonemes except for the four approximants and the two affricates.

Five female subjects served as both talkers and listeners; when one subject produced the tokens, the other four subjects listened and wrote down what they heard. The sixteen consonants were spoken before the vowel */a/*, as is f*a*ther. Each talker read out a list of 200 nonsense syllables, with the probability of occurence of each syllable being 1 in 16, and with the order being randomized within and between lists. The syllables were spoken at an average rate of one every 2.1 seconds. The listeners were forced to respond for each syllable, even if they had to guess.

The talker's speech was amplified, then filtered if desired, then mixed with noise, and then amplified again and presented to the listeners through earphones. The S:N was varied by changing the gain in the speech channel. When the speech was filtered, the S:N corresponded to +12 dB for unfiltered speech. The gain to the VU-meter was fixed so that the talker could keep her voice at a reasonably constant value.

With four listeners, there were 800 syllable-response events per talker. In all, with pooling the five talkers, there were 4000 syllable-response events for each condition tested. These results were entered into tables called "confusion matrices", where the table displayed the syllables that were spoken and the corresponding syllables the listeners had chosen as responses. Thus, there were 256 (16x16) cells in each table, each cell corresponding to a possible syllable-response pair. The number entered in each cell was the raw frequency with which each response-pair occurred. One table was produced for each S:N and filtering condition.

When analyzing the confusions that the listeners made, the authors looked at the articulatory features of the consonants. A feature can be viewed as a "phonetic property that can be used to classify sounds" (Ladefoged, 1982). If it can be used to describe a single phonological opposition in a language, such as a *voiced* (/b/) versus an *unvoiced* (/p/) sound, a feature is known as a *binary* feature. If a feature is used to classify a sound in terms of more than two possibilities, such as the *Place of Articulation* feature, in which a sound could be classifed as 'labial' (/p/), 'alveolar' (/t/), 'palatal' (/j/), or 'velar' (/k/), it is called a *multivalued* feature. Features can be used to classify the phonological oppositions that occur in languages or to describe their phonetic structures (Ladefoged, 1982). Although articulatory features are related to articulatory gestures, "specific theories of what distinctive features there are have been postulated in an effort to account for regularities in the sound systems of languages, not articulation itself" (Caplan, 1992). The features Miller & Nicely (1955) investigated were: (1) *Voicing* (e.g. the feature that is used to specify the distinction between phonemes such as /b/ vs /p/), (2) *Nasality* (e.g. the feature that is used to specify the distinction between phonemes such as /n/ vs /t/), (3) *Affrication* (e.g. the feature that is used to specify the distinction between phonemes such as /t/ vs /s/), (4) *Duration* (the feature used by the authors to specify the distinction between the phonemes /s,ʃ,z,ʒ/ and the other 12 consonants), and (5) *Place of Articulation* (the feature described above that is used to specify the distinction between phonemes such as /p/ vs /t/). Each feature was given an articulation score, or probability of the feature being perceived correctly, for each confusion matrix. As well, a covariance measure of intelligibility was applied to each of the linguistic features in order to measure the transmission of information about each feature.

1.3.2 Competing Noise and Speech Perception

Although competing noise negatively affected the amount of information transmitted with respect to all of the articulatory features, it was found that voicing and nasality were much less affected by random masking noise than were the other features. The most affected by competing noise was the feature place of articulation. Whereas voicing and nasality are discriminable in S:N conditions as poor as -12 dB, place of articulation was difficult to distinguish when S:N dropped below 6 dB. In the presence of masking noise, the accuracy of recognition of affrication and duration was far less than for voicing and nasality, but better than for place of articulation. Approximately 50% of voicing and nasality information was transmitted at -12 dB S:N, whereas transmission of affrication and duration information was reduced to 50% at -3 dB S:N.

1.3.3 Frequency Distortion and Speech Perception

Miller & Nicely (1955) found a significant correspondence between the effects of masking by random noise and filtering by low-pass filters on the perception of the different articulatory features. The authors point out that this seems logical if one thinks of the masking noise as a kind of low-pass filtering system, by which the relatively weak high-frequency components of speech are masked more effectively. As with masking by random noise, with low-pass filtering, the perception of voicing and nasality cues was superior to the perception of place of articulation cues. While only 60% of place of articulation information is transmitted when the cutoff frequency of the low-pass filter is approximately 5000 Hz, approximately 90% of voicing and nasality information is transmitted with this cutoff frequency. When the cutoff frequency of the low-pass filter is 300 Hz, 60% of voicing and nasality information is still transmitted while close to 0% of place of articulation information is transmitted. The perception of affrication and duration cues is also superior to perception of place of articulation cues, but is inferior to the perception of voicing and nasality. The main difference between random noise and low-pass filtering is that with low-pass filtering, the results for affrication and duration differ slightly from each other. The information transmitted by affrication is somewhat less negatively affected by low-pass filtering than is the transmission of duration information.

Unlike random masking noise and low-pass filtering which have similar effects of speech perception, high-pass filtering yields quite different results. Overall, with high-pass filtering, the perception of all the articulatory features deteriorates in the same way as the low frequencies are eliminated to a greater and greater extent, so that there is very little chance of predicting specifically what kind of error will occur. However, duration is a little more robust than the other features. When the cutoff frequency of the high-pass filter is set at 2000 Hz, approximately 50% of the duration information is transmitted whereas only approximately 35% of the information associated with the other features is transmitted. The authors speculated that duration is relatively well preserved because the four English fricatives (the alveolars and palato-alveolars) are inherently long in duration and are characterized by high-frequency energy, such that they can still be heard with high-pass filtering.

The results from this study point to a notable difference between low- and high-pass filtering; "low-pass filters affect the several linguistic features differentially, leaving the phonemes audible but similar in predictable ways, whereas high-pass filters remove most of the acoustic power in the consonants, leaving them inaudible and, consequently, producing quite random confusions" (p.313). Because of the predictability of low-pass errors, they therefore can carry some information, and if there is sufficient context and redundancy in the communication message, the errors can be corrected more easily than if the errors were completely random, as with the errors observed in conditions of high-pass filtering.

1.4 The Mandarin Language: Li & Thompson (1981), Howie (1976), and Dow (1972)

1.4.1 Mandarin Language and Dialects

Mandarin is spoken in Northern China, including Beijing, and in Taiwan. It is spoken by a larger percentage of China's population than any other language. In 1955, the government of the People's Republic of China "proclaimed a national language embodying the pronunciation of the Beijing dialect, the grammar of northern Mandarin, and the vocabulary of modern vernacular literature" (Li & Thompson 1981, p.1). This national language is known as "Putonghua", and is the language of instruction in the school system. As well as learning to read and write with Chinese characters, students are also taught to read and write Mandarin with what is called "Pinyin" romanization. Taiwan also proclaimed a national language based on the Beijing dialect, and it is known as "Guoyu". Mandarin includes both Putonghua and Guoyu. Mandarin has four subgroups of dialects, such that of the seven dialect groups that exist in China, these four have the highest degree of mutual intelligibility.

1.4.2 Mandarin Phonology

Traditionally when describing the phonology of Mandarin, the structure of the syllable is broken down into units called 'initials', 'finals' and 'tones'.

Initials

In Mandarin, the initial is essentially the consonantal beginning of the syllable, or what is known as the syllable 'onset' in standard phonology. There are twenty-two consonants in Mandarin, twenty-one of which can be initials. The velar nasal is the only Mandarin consonant that cannot be an initial. There are no consonant clusters in Mandarin, therefore the initial is always comprised of a single consonant. Some syllables do not have an initial consonant; in these cases the initial is described as the *zero initial.* Table 1-1. describes the twenty-one initials of Mandarin using both Pinyin romanization and the phonetic symbols used by the International Phonetic Association (IPA), with IPA symbols in the left-hand columns and Pinyin in the right-hand columns.

Table 1.1. Mandarin Initial Consonants

		Bilabial	Labiodental	Alveolar	Retroflex	Palatal	Velar
Stop	aspirated	pʰ p		tʰ t			kʰ k
	unaspirated	p b		t d			k g
Affricate	aspirated			tsʰ c	tʂʰ ch	tɕʰ q	
	unaspirated			ts z	tʂ zh	tɕ j	
Fricative	voiceless		f f	s s	ʂ sh	ɕ x	X h
	voiced						
Nasal	voiced	m m		n n			
Approximant	voiced			l l	ɻ r		

As can be seen in the above table, Mandarin has eleven unvoiced affricates and fricatives, as opposed to English, which has only five unvoiced fricatives and affricates. Unlike English, in Mandarin it is aspiration and not voicing that is phonemically distinctive.

Finals

The final (known as the 'rhyme' in standard phonology) represents the part of the syllable that occurs following the initial. There are thirty-seven finals in Mandarin, most of which contain only vowels. The vowel occurs in what is known as the syllable 'nucleus' in standard phonology. Only two consonants can be included in the final: the alveolar nasal [n] and the velar nasal [ŋ]. These consonants can only occur at the end of the final, in what is known as the 'coda' position in standard phonology. The finals are presented in Table 1-2., listed as IPA symbols.

Table 1-2. Mandarin Finals

ɿ,ʅ,ɚ	A	ə	o		ai	ei	au	ou	an	ən	aŋ	əŋ	
i	iA			iɛ			iau	iou	iɛn	in	iaŋ	iŋ	
u	uA		uo		uai	uei			uan	uən	uaŋ	uŋ	uəŋ
y				y					yɛn	yn			

Tones

There are four tones in Mandarin. Tone is an essential part of syllable-formation in Mandarin. Just like a segmental phoneme, tone conveys lexical meaning. It can be described as a relative, contrastive pitch pattern associated with a syllable.

The pitch pattern of Tone 1 is described as *high level*, Tone 2 as *high rising,* Tone 3 as *falling-rising,* and Tone 4 as *high falling.* Following Y.R. Chao (1968), the tones' pitch patterns are also described in terms of numbers from one to five, one being the lowest pitch and five being the highest pitch (Howie, 1976). Thus Tone 1 is given the number 55, meaning that the pitch of the syllable begins and ends at level 5, remaining high and level throughout. Tone 2 is given the number 35, Tone 3 is given the number 214 (pitch begins at level 2, falls to level 1, and then rises up to level 4), and tone 4 is given the number 51.

The four tones above refer to the four tones found in isolated syllables; during connected speech, the tonal contours are affected by adjacent tones and by sentence intonation (Howie, 1976). The present study focuses only on the four tones found within citation syllables.

Due to the constraints on the segmental construction of the Mandarin syllable, approximately 400 different segmental syllables are possible. With the addition of tone, and the "accidental" gaps in the distribution of these four tones, just under 1200 differentiated syllables occur as morphemes; there seem to be no systematic constraints on the distribution of the four tones in isolated monosyllabic morphemes (Howie, 1976).

1.5 Acoustical Studies of Mandarin Tones: Howie (1976)

The main purpose of Howie's (1976) study was to investigate the acoustical properties of Beijing Mandarin tones, as they occur in citation forms of monosyllabic morphemes in a controlled environment.

Thirty-four sets of monosyllabic morphemes minimally distinguished by tone, showing a wide range of syllable structures, were spoken by a young male Mandarin speaker and recorded. They can be classified into nine types of syllable structures: "Type 1", with initial syllabic vowel, "Type 2", with initial non-syllabic vowel, "Type 3", with initial non-syllabic vowel and final nasal consonant, "Type 4", with initial voiceless fricative, "Type 5", with initial voiced continuant, "Type 6", with initial aspirated stop, "Type 7", with initial unaspirated stop, "Type 8", with initial aspirated affricate, and "Type 9", with initial unaspirated affricate.

The course of the fundamental frequency during the entire voiced part of the syllables was measured from spectrograms of the recorded utterances. For each syllable, the fundamental frequency values were plotted on graphs of identical dimensions, with frequency represented on a logarithmic scale on the vertical axis, and percent of duration of the voiced part of the syllable on a linear scale on the horizontal axis. The plotted points on the graph were then connected to form a curve to portray the pitch pattern of the syllable. Average curves of syllables of the same type and tone were then drawn, to achieve average curves for the four tones in the nine syllable types.

Each tone group displays the same similarities and differences between the syllable types. When looking at each tone group individually, syllable structure types 1, 6, and 7 have similar curves, types 2, 3, and 5 have even more pronounced similarities, as do types 4, 8, and 9. There are some differences in the shape of the curve between the nine syllable type curves for each tone, and these differences seem to be due to the presence or absence of a segment preceding the syllabic vowel, and with the kind of segment that occurs there. For example, with initial vowels, tones 1 and 4 have a longer rise time than with initial stops. Tones 2 and 3 with initial vowels do not dip as low as with initial stops. Also, there are slight differences in tone contour when there is an initial unaspirated stop versus an initial aspirated stop.

The most recognizable differences in curve shape are observed between syllable structure Types 2, 3, and 5, with initial voiced consonants (/m/, /n/, /l/) or non-syllabic vowels, and the other types. Type 2, 3, and 5 curves have humps, or shoulders near the beginning of the curves of every tone, while after the hump, the rest of the curve is similar to the entire curve of the same tone in all the other types.

It was also found that for Types 2, 3, and 5, the mean durations of the voiced part of the syllable were from 50 to 60 percent longer than for all other types, while the mean durations of the other types were nearly identical for each tone. The author interprets the portion of the curve preceding the turning point of the hump as an anticipatory movement of voice pitch occurring during the initial voiced consonant or non-syllabic vowel. This theory suggests that "the domain of tone in Mandarin is not the entire voiced part of the syllable, as it is traditionally described, but rather is confined to the syllabic vowel and any voiced segment that may follow it in the syllable" (p.218).

Generalized average curves of the four tones in all nine syllable types (spoken by a male speaker) give the following mean durations of the voiced part of the syllable on each tone: Tone 1, 225 milliseconds; Tone 2, 253 milliseconds; Tone 3, 269 milliseconds; Tone 4, 245 milliseconds. Tone 1 in Howie's study may therefore sound slightly shorter, and Tone 3 slightly longer, than Tone 2 and Tone 4. The general pitch contour for Tone 1 is essentially level, with fundamental frequencies starting and ending at approximately 150 Hz. For Tone 2, the fundamental frequency starts at approximately 110 Hz, starts rising immediately and reaches approximately 150 Hz at 80% of the tone's duration, and remains at this frequency for the last 20% of the tone. Tone 3 also begins at approximately 110 Hz, but starts falling immediately, reaches its low of approximately 90 Hz at its halfway mark, and begins rising again and reaches 120 Hz by its finish. Tone 4 starts at approximately 160 Hz, starts falling immediately, reaches approximately 130 Hz by its halfway point, and continues to fall until approximately 110 Hz at its finish.

To summarize, the overall pitch range of the four tones was found to be approximately ten semitones. Tone 1 remains high in the upper five semitones, Tone 2 rises through the upper five semitones, Tone 3 remains within the lower five semitones, and Tone 4 falls through the upper five semitones.

1.6 Tonal Perception

1.6.1 Howie (1976)

In his book, Acoustical Studies of Mandarin Vowels and Tones, John Howie (1976) describes several of his studies on Mandarin tonal perception. The first experiment was designed to verify the hypothesis that when isolated from their context, Mandarin tones in citation form can be correctly identified. Nine subjects listened to a recording of four sets of tonally differentiated morphemes in isolation, produced by a young male Mandarin speaker. For each set, in which five tokens each of the four stimuli of the set were randomly presented, the listener identified which tone was presented. For each set, three subjects scored 100 %, and the mean scores for the four sets ranged from 92 % to 100 %. These results demonstrate that without any help from context, the perception of tones in monosyllabic utterances by Mandarin listeners is highly accurate.

For the next two experiments, synthetic tones were produced by using generalized average fundamental frequency curves for each tone. These generalized tonal curves were obtained by plotting the course of the fundamental frequency throughout the voiced segment of a syllable, for each of fifteen sets of monosyllabic morpheme pairs minimally distinguished by tone. An average curve for each tone was then obtained. A more in-depth description of this averaging method is discussed above in section 1.5. The four synthetic tones were imposed on the Tone 1 syllable 'bao', recorded by the same young male Mandarin speaker.

In both experiments, twelve subjects listened to five tokens of each of the four stimuli. In the first experiment, the carrier phrase was deleted and the stimuli were heard in isolation, and in the second experiment the carrier phrase remained. Recognition was 95.4% correct with the citation syllables in isolation. However, with the citation syllables in the carrier phrase, intelligibility dropped to 81.3% correct, and more than half of the mistakes consisted of identifying Tone 3 as Tone 2. The experiment with the citation syllables in isolation, at least, supports the hypothesis that fundamental frequency provides effective cues for the perception of the Mandarin tonal distinctions. It also, then, validates the generalized fundamental frequency curves as acoustic descriptions of Mandarin tones in isolated citation syllables. Because the generalized curve of each tone was obtained from curves of tones exhibiting variations in shape and syllable structures, and because these variations were neutralized in the generalized curve, it has been shown that "only the most essential features of a tone--those shared by syllables of all structures--are necessary for its perception" (p.241).

The author goes on to explain that the lower recognition when the citation syllable was uttered with a carrier phrase may be due to the effects of tone sandhi, or the interaction of tones within the sentence. The neutral tone directly following the citation syllable in the carrier phrase is influenced by the tone of the citation syllable. All four synthetic tones were imposed on a Tone 1 syllable, and normally a neutral tone has a relatively low pitch when preceded by Tone 1. When preceded by Tone 3, a neutral tone has a relatively high pitch, and when preceded by Tone 2, a neutral tone normally has a relatively mid pitch. Because the carrier phrase for all the synthetic tones was produced with a neutral tone with a relatively low pitch (it originally followed a Tone 1 syllable), the neutral tone following the syllables with synthetic Tones 2, 3, and 4 will therefore sound "wrong". The author hypothesizes that listeners may have interpreted the sequence of synthetic Tone 3 with a low neutral tone as a "deviant" sequence of Tone 2 and a mid neutral tone.

The last experiment Howie (1976) describes involves suppressing a citation syllable's tone. In the first test, the tonal contours of a set of four tonally differentiated morphemes were suppressed by imposing on them a perfectly level pitch of 128 Hz. In the second test, the tonal contours were suppressed by substituting an aperiodic sound source, making the syllables voiceless, or whispered. Six listeners were asked to identify the tone carried by these four syllables, each presented randomly five times. The percentage of "correct" responses was not much greater than chance. With the monotone syllables, recognition was 30.8% correct, and with the whisper syllables, recognition was 39.2% correct.

This last experiment confirms the hypothesis that in Mandarin, at least, pitch is the primary feature in the perception of tones. The "whispered" syllables were slightly better recognized than the monotone syllables, and the author postulates that "when the distracting effect of the monotone pitch is absent the concomitant features of intensity and duration can, in the "whispered" syllables, play a greater role in the perception of the tones" (p.244). He goes on to explain that in listening to the "whispered" syllables, a non-Chinese speaker can hear the sharply falling pitch of Tone 4 as a sharp drop in the intensity of the hiss, but the Mandarin listeners seemed not to make much use of any features other than pitch when identifying tones, judging from their intelligibility scores. However, it was found that the concomitant features of Tone 4 were twice as effective in the "whispered" syllables as they were in the monotone syllables.

1.6.2 House (1990)

David House (1990), in his book Tonal Perception in Speech, investigates the perception of tonal movement, or pitch, in speech. The study addresses the question of how tonal movements are coded by the auditory system and then changed into linguistic or paralinguistic categories. To answer this question, tonal perception experiments were conducted using Swedish listeners, and evidence was taken from the literature on the perception of word tones and word accents, on the perception of pitch as studied by psychoacousticians, and on the perception and modeling of intonation.

The author developed a new hypothesis of tonal perception based on central processing theories and models of pitch perception. First, a rough power spectrum of the stimulus is obtained through a first-order spectral analysis of the speech wave. Following this, a central processor extracts the pitch on the basis of the spectral analysis, using pattern recognition techniques. The author formulated his main hypothesis as two working hypotheses. The Spectral Constraint Hypothesis proposes that sensitivity to tonal movement, or pitch perception, is "greatest during areas of relative spectral stability and least during areas of spectral and intensity change" (p.145), such as consonant release or quick formant transitions at the beginning of a vowel. The Tonal Movement Coding Hypothesis proposes that "tonal movement during spectral stability is coded as movement configurations (e.g. rise or fall) while tonal movement during areas of spectral change is coded as pitch levels (e.g. high or low) which can then be stored in short-term memory" (p.145).

Perception experiments were conducted to test these hypotheses in which tonal contours were varied in relationship to segmental boundaries. In a first experiment, it was found that listeners categorized rise-fall and fall-rise contours as movement configurations when these contours occurred during periods of spectral stability. However, when the contour occurred in an area of spectral change, the overall tendency was to categorize the tone contour as a pitch level. In a second set of experiments, it was found that the categorization of a falling contour was highly dependent on the timing of the fall relative to spectral changes near segmental boundaries. Both these experiments therefore support House's hypotheses.

The author also describes a model of optimal tonal feature perception. Level features are given perceptual priority over movement contour features. Three constraint conditions are proposed for the optimal perception of contour features: movement must occur through a period of relative spectral stability in the vowel, movement must be synchronized with vowel onset so that the beginning of the rise or fall occurs 30-50 milliseconds into the vowel, and vowel duration must be greater than 100 milliseconds.

Tonal perception in listeners who are hearing-impaired was also discussed. From evidence in the literature, it appears that the hearing-impaired listener with a sensorineural hearing loss may have more difficulty using tonal movement cues for coding stress, intonation, tone and speaker mood than do normally hearing listeners. The author suggests that the inability to process correctly the tonal movement in relationship to syllable and segment boundaries, as well as absolute threshold changes and reduced frequency and temporal resolution, may contribute to the decreased sensitivity to tonal movement perception.

1.7 Hypotheses

In this chapter, we have discussed the effects that frequency filtering and competing noise have on speech perception in English. Also reviewed was the phonology of Mandarin and some acoustical studies of the four Mandarin tones. Studies of the perception of tone also demonstrated that fundamental frequency is the primary cue for the perception of tone. A hypothesis of tonal perception based on central auditory processing theories and models of pitch perception was also discussed.

This study investigates the effects that low-pass filtering and competing noise have on the perception of Mandarin initial consonants and tones.

The following hypotheses were tested:

Hypothesis 1: Low-pass filtering will not affect the perception of tone in Mandarin.

Reasoning: Tone is mainly perceived as changes in the fundamental frequency which will not be affected by the low-pass filtering.

Hypothesis 2: Competing white noise will not affect the perception of tone as greatly as it affects the perception of consonants in Mandarin.

Reasoning: Competing noise can be viewed as a kind of "low-pass filter", as discussed in section 1.3.3; therefore, it will not mask the fundamental frequency as much as it masks the consonants, or the relatively weak high-frequency components of speech.

Hypothesis 3: The perception of aspiration and nasality cues in Mandarin will be superior to the perception of place of articulation and 'stop' cues in the presence of background noise and low-pass filtering.

Reasoning: Accompanying Research on consonantal confusions in the English language by Miller & Nicely (1955) for the same or similar features is the basis for this hypothesis.

Hypothesis 4: Competing noise will cause more perceptual confusions among consonants in Mandarin than in English.

Reasoning: There are relatively more high-frequency unvoiced consonants in Mandarin than in English, as discussed in section 1.4.2.

Hypothesis 5: The degree of consonantal and tonal confusion in Mandarin will vary with tone.

Reasoning: The average duration of the four tones presented in this study would suggest that Tone 4 and Tone 3 should be maximally distinguishable because Tone 4 is shorter, and Tone 3 is longer than Tones 1 and 2 (see Appendix A). The average intensity of the four tones would suggest that consonants in a Tone 4 or Tone 1 syllable should be easier to perceive correctly, since the syllables in the present study produced with Tone 4 were of the highest intensity, followed by syllables produced with Tone 1, then Tone 2, then Tone 3 (see Appendix A).

2. METHOD

2.1 Design

Two experiments, one to study consonant perception and another to study tone perception, were each conducted using the same six test conditions. The six experimental conditions varied in terms of the level of competing noise (none, low noise, high noise), and filtering (present or absent). The six conditions were as follows:

1. Quiet, Unfiltered (QU).
2. Quiet, Filtered (QF).
3. Competing noise (easy listening condition), Unfiltered (N1U).
4. Competing noise (easy listening condition), Filtered (N1F).
5. Competing noise (difficult listening condition), Unfiltered (N2U).
6. Competing noise (difficult listening condition), Filtered (N2F).

All subjects completed both experiments. Each subject attended three sessions, during which he/she listened to pre-recorded mono-syllables presented in each of six experimental conditions. Two experiments were run at each session: tone perception (T) and consonant perception (C).

The first session consisted of a basic hearing test followed by the tone perception experiment given in both quiet conditions (QUT and QFT), followed by the consonant perception experiment given in both quiet conditions (QUC and QFC). Before both the QUT and QUC conditions a short practise was given. Before the QUT condition there was a pre-recorded example given of each of the Mandarin tones.

The second session consisted of the tone perception experiment given in both the easy S:N conditions (N1UT and N1FT) followed by the consonant perception experiment given in both the easy S:N conditions (N1UC and N1FC). As in the first session, a short practise was given before the N1UT and N1UC conditions.

The final session consisted of the tone perception experiment given in both the difficult S:N conditions (N2UT and N2FT), followed by the consonant perception experiment given in both the difficult S:N conditions (N2UC and N2FC). Again, the short practise was given before the unfiltered conditions, N2UT and N2UC.

2.2 Subjects

Ten subjects (two males and eight females) participated in the study. All were native Mandarin speakers between the ages of 24 and 32 years of age. The mean age was 28.7 years. Eight of the subjects spoke Putonghua 100% of the time, four of these reporting that as children they spoke a local dialect of Mandarin at home while speaking and reading Putonghua at school. Two other subjects spoke Putonghua outside of the home and another dialect of Mandarin while at home. All considered themselves to be fluent in English, and the mean number of years living outside of China in an English-speaking country was 2.6 years, and ranged from one week to 5.5 years. They had all completed a high school education in Mandarin and the mean number of years of education in a Mandarin-language setting was 15.7 years. All subjects considered their knowledge of Pinyin romanization (taught in school) to be excellent. The mean number of years of post-secondary education was 5.7 years, ranging from 2 to 9 years. All subjects had hearing within normal limits for both ears (pure-tone air-conduction thresholds equal to or less than 20 dBHL at 250, 500, 1000, 2000, 4000, and 8000 Hz bilaterally).

2.3 Materials

2.3.1 Materials Recorded

The experimental materials consisted of 84 pre-recorded consonant-vowel (CV) syllables. There are 21 initial consonants in Mandarin (see Table 1.1) and four tones (tone 1: high, tone 2: high rising, tone 3: dipping-rising, and tone 4: high falling). Each initial consonant was followed with the vowel [a] to produce a syllable, once with each of the four tones. Some of the resulting syllables are actual Mandarin words, while some are not (see Appendix E).

A practise session for the unfiltered tone experiments (QUT, N1UT and N2UT) was given using the four syllables 'ka-tone 1', 'ka-tone 2', 'ka-tone 3', and 'ka-tone 4', presented once randomly. Two of these syllables are real Mandarin words while two are not.

A practise session for the unfiltered consonant experiments (QUC, N1UC and N2UC) consisted of each of the twenty-one syllables presented once randomly: all twenty-one initial consonants combined with [a] produced with tone 4.

During the instructions for the unfiltered tone experiments, the subject heard the pre-recorded English sentence "Chinese has four tones. Here is an example of each tone. Tone one: ma-1. Tone two: ma-2. Tone three: ma-3. Tone four: ma-4.". This recorded instruction familiarized the subject with the speaker's voice and with the relative pitches of the four tones as produced by the speaker.

2.3.2 Recording Method

The 84 mono-syllable tokens and the examples of the four tones were recorded by a Mandarin speaker while seated in a sound-attenuating, double-walled IAC booth. They were recorded using a Sennheiser model K3U microphone positioned approximately six inches from the speaker's mouth. Both the syllables and the examples of the four tones were recorded in mono, via a Proport model 656 stereo-audio DSP port interface, onto a NeXT computer system sound-recording programme, Sound Works 3.0, Version 2. The sound files were recorded at a sampling rate of 32,000 Hz and stored on the hard disk of the computer.

The speaker who produced these materials was a female native-Mandarin speaker, 34 years of age, who grew up in various areas of Northern China, speaking standard

Putonghua at school and in the home. She has been living in North America for ten years but speaks Putonghua regularly, and is a trained linguist. She completed her high school education in Mandarin and has had 12.5 years of post-secondary education.

The syllables were produced in random order in one session, at the end of a Mandarin carrier phrase, translated as "This is the character (pause) ___". A carrier phrase was used in order to minimize the drifting of the absolute frequency values of the tones as the recording proceeded. The syllables were later excised from this context. Each syllable was put in its own sound file, and the sound file was prepared with a 1.0 second interval of silence inserted before and after the speech segment. The silent interval was generated with Sound Works 3.0, Version 2.

2.3.3 Calibration of the Sound Level of the Mono-Syllables

An in-house calibration program was used to calibrate the sound level of the 84 mono-syllables. The program calculates the root mean square (RMS) of the sound pressure level of a speech signal in a sound file. In calculating the RMS.of the speech signal, any gap in speech greater than 10 msec was not included in the calculation. A gap was considered to be present when no value in the sound file exceeded 150 relative intensity units for 10 msec or longer. The average RMS in volts of all 84 syllables was calculated and found to be 0.490, with absolute values ranging from 0.154 to 0.998 Volts.

A calibration tone of 1000 Hz , of 7.071 Volts RMS was played through a loudspeaker in a sound-attenuating, double-walled IAC booth, with the desk, computer monitor and speaker set up in the booth exactly as it would be during the experiment. A Quest Electronics model 1800 Precision Impulse Integrating Sound Level Meter with a free field microphone was set up on a tripod at the same distance and height that the subject's head would be from the loudspeaker during the experiment. The sound pressure level of the 1000 Hz tone was measured using a linear scale and a third octave filter centered at 1000 Hz, and found to be 116.2 dBSPL. Knowing that the mean RMS of the

84 syllables is 0.490 Volts and that the RMS of the calibration tone is 7.071 Volts, using the equation 20 log 0.490/7.071 = -23.184 dB gives the mean sound pressure level of the 84 syllable sound files to be: 116.2 dBSPL - 23.2 dBSPL = 93.0 dBSPL.

Since the desired presentation level of the 84 mono-syllables was to be the average level of conversational speech in English, which is 70.0 dBSPL, or 50.0 dBHL (Davis, 1947), the level of the stimuli needed to be attenuated by 23.0 dB (93.0 - 70.0). This attenuation was achieved using a Tucker-Davis Technologies (TDT) Model PA4 programmable attenuator.

2.3.4 Measurement of the Sound Level of the Competing Noise

Gaussian white noise generated by a TDT Model WG1 waveform generator was played through a speaker in the sound-attenuating double-walled IAC booth, and using the same set-up and method of measurement as above, was measured to be 87.5 dBSPL. It was then attenuated to achieve the desired S:N following the method described above.

2.3.5 Characteristics of the Acoustic Filter

To mimic the effect on pure-tone hearing thresholds of a moderate high frequency hearing loss, a low-pass filter was created using the TDT model PF1 programmable filter. This filter was based on an audiogram with thresholds as seen in Table 2-1.

Table 2.1 Bilateral Thresholds on which Low-Pass Filter is Based

	Test Frequency					
	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000Hz
dBHL	0	0	10	30	45	60

The actual output of this filter was measured by finding the difference between the sound pressure level of warbled tones from 100 Hz to 8000 Hz as presented unfiltered versus filtered. For instance, for a tone of 1000 Hz, attenuation was measured to be 10.2 dB, whereas for a tone of 4000 Hz, attenuation was measured to be 42.1 dB. The set-up of the booth and the method of measurement were the same as described above in section 2.3.3. The output of the filter is described in Table 2-2.

Table 2-2. Low-Pass Filter Attenuation Values

Centre Frequency (Hz) of 1/3 Octave Band	Attenuation (dB)
100	2.0
160	-0.2
200	2.4
250	2.7
315	2.4
400	3.5
500	3.9
630	5.4
800	9.2
1000	10.2
1250	11.8
1600	16.3
2000	26.8
2500	29.0
3100	30.2
4000	42.1
5000	47.2
6300	53.6
8000	53.9

For the filtered conditions, the white noise (as well as the syllables) was filtered to mimic how a listener with a moderate high-frequency hearing loss would hear background noise.

2.4 Procedures

The practise and experimental stimuli were presented to the subject through a Maico Hearing Instruments speaker positioned directly to the left of the subject, one metre from the centre of the subject's head. The subject sat at a small table facing a computer screen. The subject was seated in a sound-attenuating, double-walled IAC booth, while the experimenter was outside the booth, seated at a computer from which the experiment was controlled.

During the tone perception experiments, the subject had to decide which of the four Mandarin tones was heard. During the consonant perception experiments, the subject had to decide which of the twenty-one Mandarin initial consonants was heard.

The practise and experimental stimuli were presented at 70 dBSPL. The competing noise was presented at one of four levels. For the Tone experiment, the noise was presented at 70 dBSPL (N1) or at 74 dBSPL (N2), respectively 0 dB S:N or -4 dB S:N. For the Consonant experiment, the noise was presented at 44 dBSPL (N1) or at 48 dBSPL (N2), respectively +26 dB S:N or +22 dB S:N. These levels were chosen to provide two different listening conditions: one in which listening became slightly more difficult than usual, and one in which listening became very difficult. A pilot trial with three subjects was performed to determine appropriate S:N conditions to achieve these effects.

At the first session for the quiet conditions, the practise for the tone experiment was continued until the subject scored 100 % correct. None of the subjects needed more than two practise sessions to reach the 100 % correct criterion. The practise for consonants was given no more than twice. After the first practise, the subject was asked if he or she would feel more "comfortable" having a second practise run before testing began. At the next two sessions, the practise was given only once (see Appendix B for intructions to subjects).

2.5 Experimental Task

During the tone perception experiments, the subject listened to 84 mono-syllables randomly presented three times each, and decided which of the four Mandarin tones was heard. On the computer screen in front of the subject were four boxes, each one containing a label for one of the four tones, such as 'Tone 1', or 'Tone 2'. After a syllable was heard, the subject indicated which tone was heard by using the computer mouse to highlight one of the boxes. During the consonant perception experiments, the subject again listened to the 84 mono-syllables randomly presented three times each, and decided which of the twenty-one Mandarin initial consonants was heard. On the computer screen in front of the subject were 21 boxes, each containing one of the 21 syllables spelled in Pinyin Romanization, and the subject again indicated which consonant was heard by highlighting the corresponding box.

No feedback was given to the subject on the accuracy of his/her choice during the experiments. However, during the practise sessions, the box that the subject highlighted turned green if the response was correct and orange if the response was incorrect.

2.6 Recording the Responses

The computer monitor and keyboard in the sound-booth used by the subject were connected to the computer at which the experimenter sat. Stimuli were presented and subject responses were recorded using the CSRE 4.2 experimental control program.

3. RESULTS

3.1 Consonant Perception

The results from the consonant experiments will be presented in the form of confusion matrices. The data from all ten subjects have been grouped together. Tables 3-1 to 3-6 summarize the data for consonant perception in each of the six test conditions. Including all ten subjects, each consonant was judged 120 times in total in each test condition. Each matrix records 2520 subject responses. (Results for individual subjects and for group data for consonant perception in each of the six test conditions for each tone can be found in Appendix C).

For each matrix, the target consonants correspond to rows, while the consonants that the subjects chose as their responses correspond to columns. The number written in each cell indicates the number of times that the stimulus-response pair was observed. By adding the numbers along the main diagonal from top left to bottom right, the total number of correct responses can be obtained.

As shown by Tables 3-1 to 3-6, responses became less accurate as low-pass filtering was introduced, and became increasingly less accurate as S:N condition worsened. Figure 3-1 gives the mean percentage correct for consonant perception in each of the six test conditions. Figure 3-1 demonstrates that the low-pass filtering and the easy S:N condition (N1) had similar effects on the accuracy of responses, while the conditions with both background noise and filtering had the most significant negative effect on the accuracy of responses. Figure 3-2 gives the mean percentage correct for consonant perception for tones 1-4 in each noise condition. This figure demonstrates that subjects in general responded most accurately to consonants in syllables carrying Tone 4, and least accurately to consonants in syllables carrying Tone 3. It appears that subjects in general responded similarly to consonants in syllables carrying Tones 1 or 2.

Table 3-1. Confusion Matrix for Condition: Quiet, Unfiltered, All Subjects, All Tones

	b	c	ch	d	f	g	h	ji	k	l	m	n	p	qi	r	s	sh	t	xi	z	zh
b	118			1					1												
c		103	14														1			2	
ch		4	115														1				
d				118				1										1			
f	21				99																
g				21		99															
h							62		9				47					2			
ji								120													
k		3							116				1								
l										113		1			6						
m											118	2									
n												119			1						
p	1												119								
qi		3	3											111					3		
r										10					109						1
s																82	11			22	5
sh			1													1	118				
t									2				17					101			
xi								56						2					62		
z		1															1			107	11
zh																				13	107

Percentage Correct: 87.9365 %

Table 3-2. Confusion Matrix for Condition: Quiet, Low-Pass Filtering, All Subjects, All Tones

	b	c	ch	d	f	g	h	ji	k	l	m	n	p	qi	r	s	sh	t	xi	z	zh
b	112			3	4	1															
c		50	46						1				11					11		1	
ch		21	78						1				2					18			
d	1			105	1	1										1	7	4			
f	31			1	85												2	1			
g				34		77										1	4			3	1
h	1	6	4				58		2				35					14			
ji								93	1										26		
k		16	6						71				8					19			
l										110		5			5						
m										1	110	9									
n											4	116									
p									1				106					13			
qi	1	1	3			1							1	109					4		
r							1			9					105					3	2
s		1	2													40	34			20	23
sh			1													7	104		1	3	4
t									2				27					91			
xi								44						2				1	73		
z		1						2								11	17		1	49	39
zh																4	15			24	77

Percentage Correct: 72.1825 %

Table 3-3. Confusion Matrix for Condition: S/N = +26 dB, Unfiltered, All Subjects, All Tones

	b	c	ch	d	f	g	h	ji	k	l	m	n	p	qi	r	s	sh	t	xi	z	zh
b	92			1	25					1			1								
c		18	9				1		2				11		1	1		77			
ch		8	110										1				1				
d	1			109												4				4	2
f	29			2	88											1					
g				9		79			2		1					2	1			20	6
h		4	2				35		12			1	33					33			
ji								99						2					19		
k		4	3				1		73				9					29		1	
l										113		2			5						
m											116	4									
n				1								119									
p		2					1					1	94					22			
qi								2						116					2		
r						1				6					106		1			6	
s				5		1										33	11			60	10
sh																4	116				
t		5	1				2		4				19			1	1	87			
xi								85						1					34		
z				1												10	6			84	19
zh															1					16	103

Percentage Correct: 72.381 %

Table 3-4. Confusion Matrix for Condition: S/N = +26 dB, Low-Pass Filtering, All Subjects, All Tones

	b	c	ch	d	f	g	h	ji	k	l	m	n	p	qi	r	s	sh	t	xi	z	zh
b	75			10	28	1							3				3				
c		18	12				6		12				29				1	42			
ch		18	23		1		3		14				21			1		38		1	
d	4			89	3	4										6	4			7	3
f	25			7	67	8			2				2			3	2			4	
g	2			34	6	30			2							8	11			18	9
h		7	6		2		33	1	21				24					26			
ji								77						1					42		
k		19	8	1			8		24			1	20					39			
l										89	1	8			22						
m										6	90	24									
n								1		5	10	101		1	2						
p	1	7	1				2		15				48					46			
qi								1						107			8		2	1	1
r							1	1		11					94		4		1		8
s		1		8	1	1			1				1			27	30			34	16
sh			5	1	3				1					4		18	68		1	6	13
t		9	8				8		14				25			1		55			
xi								64						6				1	48	1	
z		1		1	1	6		7					1			20	19		2	35	27
zh					1	4			1						1	16	31		2	33	31

Percentage Correct: 48.7698 %

Table 3-5. Confusion Matrix for Condition: S/N = +22 dB, Unfiltered, All Subjects, All Tones

	b	c	ch	d	f	g	h	ji	k	l	m	n	p	qi	r	s	sh	t	xi	z	zh
b	86			1	32	1															
c		8	6	1			1		7			3	20					74			
ch		10	108					1										1			
d				100	1			1								1	6	2		6	3
f	28			1	88					1			2								
g				22		52			4							3	2			24	13
h		8	1				24		13			1	33					40			
ji						1		90		1				3					25		
k		10	6				2		44	1			16					41			
l										110		1			9						
m										3	101	16									
n									1			119									
p			1				4						69					46			
qi			3					1						112			1		3		
r						1				6		1		1	88		4			13	6
s				9												17	8	1	2	50	33
sh														1		5	103				11
t		5					3		6				22					84			
xi								75						3					42		
z				2		3		1								14	8			67	25
zh																2	4			20	94

Percentage Correct: 63.7302 %

Table 3-6. Confusion Matrix for Condition: S/N = +22 dB, Low-Pass Filtering, All Subjects, All Tones

	b	c	ch	d	f	g	h	ji	k	l	m	n	p	qi	r	s	sh	t	xi	z	zh
b	70			14	30	2		1									2	1			
c		10	19			1	2		21				29				1	37			
ch	2	15	29		1		2		17		1		17				2	34			
d	2		1	84	1											6	4	1		11	10
f	34			7	63	6							1			4	3			2	
g	4	1	2	34	4	11		1	1			1	1			16	14	2		18	10
h		9	9		1		19	1	14				31					36			
ji								64						7	1				48		
k		11	16				7		23				24					38	1		
l				2				1		91		10			16						
m								1		10	69	39		1							
n						1		4		16	6	89			4						
p		5	7	1	1		2		15	1			35	1		1		51			
qi			2					5					1	85		3	16		5	1	2
r						1		3		12					78		6		1	6	13
s				11	1	2										27	27	2		31	19
sh		1			3			1	1					3		20	55			14	22
t		12	15				3		20				26	1			2	41			
xi								64			1			4			1		50		
z	1			2	3	3		5		1						22	28	2		22	31
zh				1	4	3						1		2		11	44		2	22	30

Percentage Correct: 41.4683 %

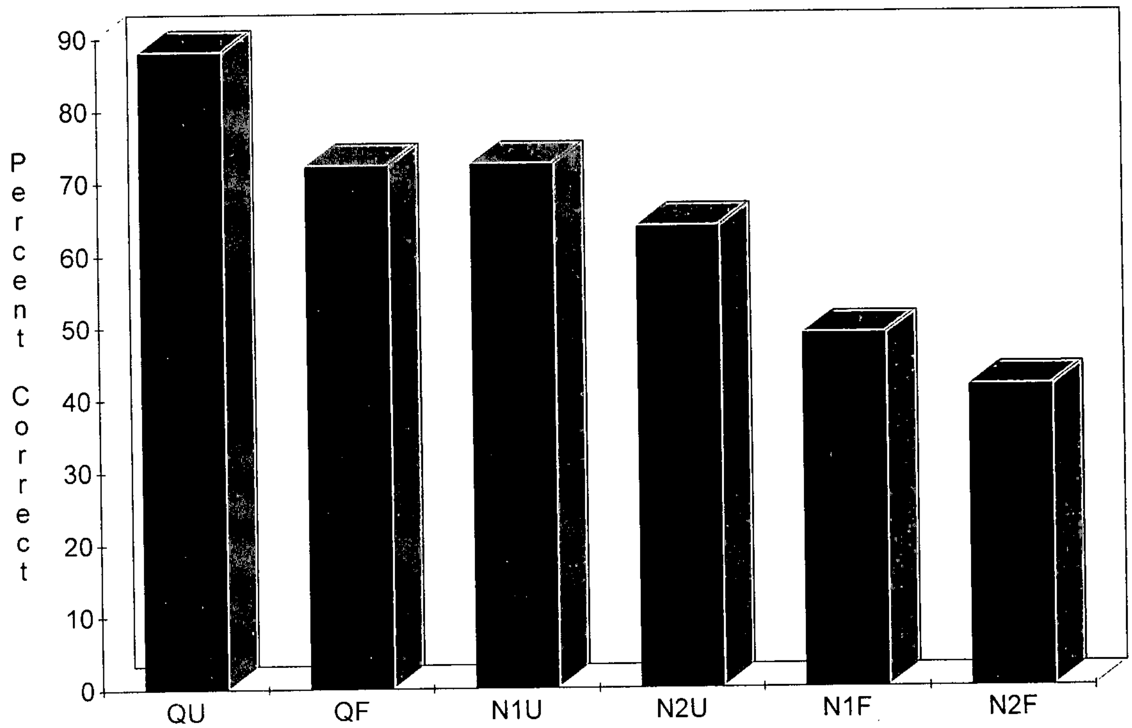

Figure 3-1. Mean percentage correct for consonant perception in each of the six test conditions.

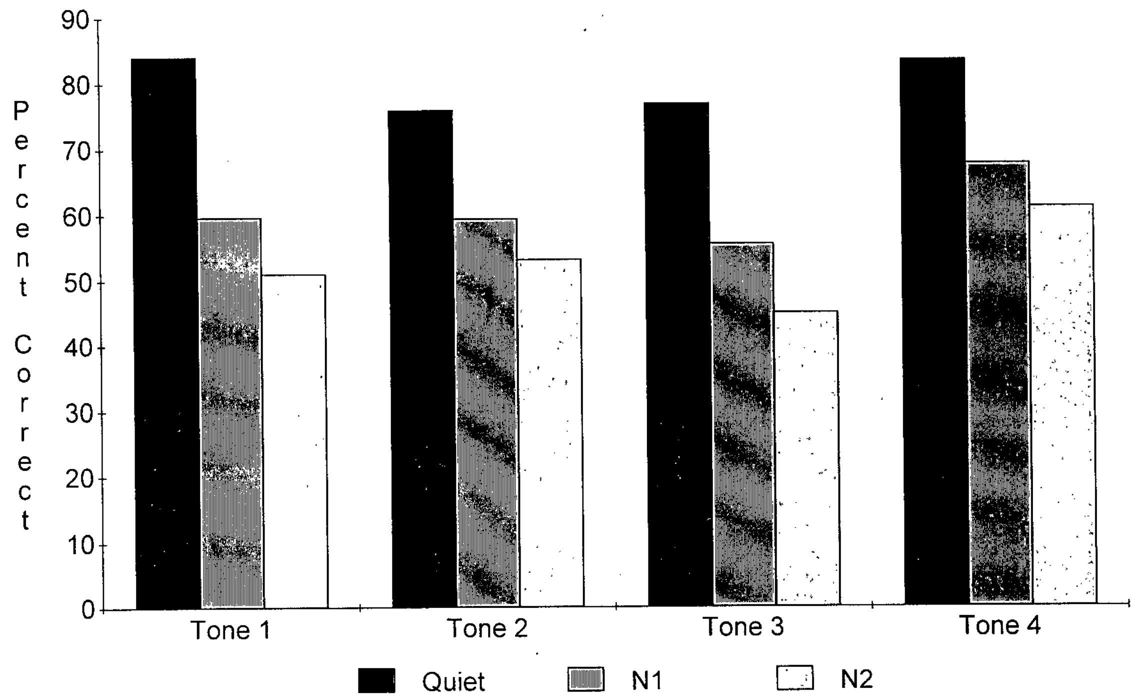

Figure 3-2. Mean percentage correct for consonant perception with tones 1-4 in each noise condition.

An analysis of variance was conducted to determine the significance of noise condition, filtering, and tone on the perception of Mandarin initial consonants. It was found that there was a significant main effect of noise condition (quiet, S:N = +26 dB, S:N = +22 dB) on the total number of correct responses ($F(2,18) = 270.87$, $p < .01$). Whether or not there was low-pass filtering was also found to be significant ($F(1,9) = 121.89$, $p < .01$). It was also found that which tone was presented significantly affected consonant perception ($F(3,27) = 45.16$, $p < .01$). A significant interaction between noise condition and tone was also found ($F(6,54) = 9.23$, $p < .01$). Finally, a significant interaction between noise condition and filtering was found ($F(2,18) = 6.14$, $p < .01$).

A Student-Newman-Keuls test of multiple comparisons demonstrated that subjects gave significantly ($p < .01$) more "correct" responses in the quiet condition (mean percentage correct of 80.06) than in the condition with background noise of +26 dB S:N (mean percentage correct of 60.58). Furthermore, they had significantly more correct responses in +26 dB S:N conditions than in +22 dB S:N conditions (mean percentage correct of 52.60).

A Student-Newman-Keuls test of multiple comparisons also demonstrated that subjects gave significantly ($p < .01$) more correct responses when the consonants were produced in a syllable spoken with Tone 4 (mean percentage correct of 70.77) than when the consonants were produced in a syllable spoken with Tone 1 or Tone 2 (mean percentage correct of 64.92 and 62.80 respectively). Furthermore, subjects gave significantly more correct responses to consonants produced in a syllable spoken with Tone 1 or Tone 2 than to consonants produced in a syllable spoken with Tone 3 (mean percentage correct of 59.15).

A third Student-Newman-Keuls test of multiple comparisons demonstrated that in the quiet, unfiltered condition (QU), subjects gave significantly ($p < .01$) more correct responses than in any other condition (mean percentage correct of 87.94). Figure 3-1 gives a summary of this data. In the conditions 'Quiet, Filtered (QF)' and 'Competing

Noise at +26 dB S:N, Unfiltered (N1U)' (mean percentages correct of 72.18 and 72.38 respectively), the subjects gave significantly more correct responses than in the condition 'Competing Noise at +22 dB S:N, Unfiltered (N2U)' (mean percentage correct of 63.73). The condition 'Competing Noise at +22 dB S:N, Unfiltered (N2U)' produced significantly more correct responses than the condition 'Competing Noise at +26 dB S:N, Filtered (N1F)' (mean percentage correct of 48.77) which in its turn produced significantly more correct responses than the condition 'Competing Noise at +22 dB S:N, Filtered (N2F)' (mean percentage correct of 41.47).

A last Student-Newman-Keuls test of multiple comparisons confirmed that in the quiet test conditions, subjects gave significantly ($p < .05$) more correct responses to consonants produced in a syllable carried by Tone 1 or 4 (mean percentages correct of 84.05 and 83.49 respectively) than to consonants produced in a syllable carried by Tone 2 or 3 (mean percentages correct of 76.83 and 75.87 respectively). Figure 3-2 provides a summary of this data. The next highest percentage of correct responses (mean percentage correct of 67.70) occurred for consonants produced in a syllable carried by Tone 4 in the easy background noise condition. Significantly less correct responses were given for consonants produced with Tone 1 or 2 in the easy noise condition or for consonants produced with Tone 4 in the difficult noise condition (mean percentages correct of 59.68, 59.37, and 61.11 respectively) than to the consonants produced with Tone 4 in the easy noise condition. Subjects gave significantly more correct responses to consonants produced with Tone 3 in the easy noise condition or to consonants produced with Tone 2 in the difficult noise condition (mean percentages correct of 55.56 and 53.17 respectively) than to consonants produced with Tone 1 in the difficult noise condition (mean percentage correct of 51.03). The significantly lowest number of correct responses occurred for consonants produced with Tone 3 in the difficult noise condition which had a mean percentage correct of 45.08.

Confusion matrices were also made to reflect the accuracy of responses in terms of linguistic features. The linguistic features chosen for analysis will be further discussed in Chapter 4, section 4.5. Tables 3-7 to 3-18 summarize the data. For each matrix, consonants were grouped together so that they fell into one of two or more categories. For example, for *nasality,* the nasal consonants /n/ and /m/ were grouped in the 'nasal' category while all the other consonants were grouped in the 'non-nasal' category. The percentage correct of recognition for nasal versus non-nasal phonemes was then calculated by adding the numbers along the main diagonal from top left to bottom right. In each matrix, rows correspond to the target category and columns correspond to the response.

Table 3-7. Confusion Matrix for *Nasality,* Quiet, Unfiltered

	Nasal	Non-nasal
Nasal	239	1
Non-nasal	1	2279

Percentage Correct: 99.9%

Table 3-8. Confusion Matrix for *Aspiration,* Quiet, Unfiltered

	Aspirated	Unaspirated
Aspirated	712	8
Unaspirated	64	1736

Percentage Correct: 97.1%

Table 3-9. Confusion Matrix for *Stop,* Quiet, Unfiltered

	Stop	Non-stop
Stop	716	4
Non-stop	79	1721

Percentage Correct: 96.7%

Table 3-10. Confusion Matrix for *Place of Articulation,* Quiet, Unfiltered

	Bilabial	Labio-Dental	Dental-Alveolar	Retroflex	Palatal	Velar
Bilabial	356					1
Labio-Dental	21	99				
Dental-Alveolar	17		770	50	1	2
Retroflex			28	452		
Palatal			3	3	354	
Velar	48		26			286

Percentage Correct: 91.9%

Table 3-11. Confusion Matrix for *Nasality,* Quiet, Filtered

	Nasal	Non-nasal
Nasal	239	1
Non-nasal	5	2275

Percentage Correct: 99.8%

Table 3-12. Confusion Matrix for *Aspiration,* Quiet, Filtered

	Aspirated	Unaspirated
Aspirated	713	7
Unaspirated	75	1725

Percentage Correct: 96.7%

Table 3-13. Confusion Matrix for *Stop,* Quiet, Filtered

	Stop	Non-stop
Stop	676	44
Non-stop	134	1666

Percentage Correct: 92.9%

Table 3-14. Confusion Matrix for *Place of Articulation,* Quiet, Filtered

	Bilabial	Labio-Dental	Dental-Alveolar	Retroflex	Palatal	Velar
Bilabial	328	4	26			2
Labio-Dental	31	85	2	2		
Dental-Alveolar	43	1	616	173	3	4
Retroflex	2		89	386	1	2
Palatal	2		2	3	351	2
Velar	44		93	15		208

Percentage Correct: 78.3%

Table 3-15. Confusion Matrix for *Nasality,* S:N +22 dB, Unfiltered

	Nasal	Non-nasal
Nasal	236	4
Non-nasal	6	2274

Percentage Correct: 99.6%

Table 3-16. Confusion Matrix for *Aspiration,* S:N +22 dB, Unfiltered

	Aspirated	Unaspirated
Aspirated	699	21
Unaspirated	113	1687

Percentage Correct: 94.7%

Table 3-17. Confusion Matrix for *Stop,* S:N +22 dB, Unfiltered

	Stop	Non-stop
Stop	596	124
Non-stop	238	1562

Percentage Correct: 85.6%

Table 3-18. Confusion Matrix for *Place of Articulation,* Quiet, Filtered

	Bilabial	Labio-Dental	Dental-Alveolar	Retroflex	Palatal	Velar
Bilabial	256	32	66	1		5
Labio-Dental	30	88	2			
Dental-Alveolar	42	1	674	98	4	21
Retroflex			58	418	3	1
Palatal			1	4	354	1
Velar	49		150	22		139

Percentage Correct: 76.5%

As shown in Tables 3-7 to 3-18, competing white noise and low-pass filtering had similar effects on consonant perception in Mandarin. Both with competing noise and low-pass filtering, the perception of nasality and aspiration cues were superior to the perception of stop cues and especially to place of articulation cues.

3.2 Tone Perception

As with the results from the consonant experiments, the results from the tone experiments will also be presented in the form of confusion matrices. The data from all ten subjects has been grouped together so that a total of 2520 responses are recorded in each matrix. Including all ten subjects, each tone was judged 630 times in total in each of the six conditions. (Results for individual subjects can be found in Appendix D). For each matrix, rows correspond to the target tone and columns correspond to the response. The number written in each cell indicates the number of times that the stimulus-response pair was observed. By adding the numbers along the main diagonal from top left to bottom right, the number of total number of correct responses can be obtained. Tables 3-19 to 3-24 summarize the data.

Table 3-19. Confusion Matrix for Condition: Quiet, Unfiltered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	627	2		1
Tone 2	7	616	5	2
Tone 3		9	619	2
Tone 4		1	3	626

Percentage Correct: 98.73 %

Table 3-20. Confusion Matrix for Condition: Quiet, Filtered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	629	1		
Tone 2	1	624	3	2
Tone 3		5	625	
Tone 4		3	1	626

Percentage Correct: 99.37 %

Table 3-21. Confusion Matrix for Condition: S:N = 0 dB, Unfiltered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	614	8	6	2
Tone 2	34	412	158	26
Tone 3	98	194	307	37
Tone 4	5	2	5	618

Percentage Correct: 77.42 %

Table 3-22. Confusion Matrix for Condition: S:N = 0 dB, Filtered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	587	20	21	2
Tone 2	47	410	149	24
Tone 3	88	215	282	45
Tone 4	6	12	17	595

Percentage Correct: 74.37 %

Table 3-23. Confusion Matrix for Condition: S:N = -4 dB, Unfiltered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	390	104	100	36
Tone 2	108	242	207	73
Tone 3	112	199	226	93
Tone 4	51	71	76	432

Percentage Correct: 51.19 %

Table 3-24. Confusion Matrix for Condition: S:N = -4 dB, Filtered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	435	96	68	31
Tone 2	109	255	198	68
Tone 3	133	210	224	63
Tone 4	49	68	75	438

Percentage Correct: 53.65 %

As shown in Tables 3-7 and 3-8, responses were highly accurate in both quiet conditions for all four tones. As shown in Tables 3-9 and 3-10, in both easy S:N listening conditions, responses to Tones 1 and 4 remained highly accurate while responses to Tones 2 and 3 began to worsen. The confusions mostly occurred between Tones 2 and 3. In both difficult S:N listening conditions, as shown in Tables 3-11 and 3-12, the total number of correct responses to Tones 1 and 4 decreased, and the total number of correct responses to Tones 2 and 3 decreased further. While the majority of incorrect responses to Tones 2 and 3 involve confusions between Tones 2 and 3, the incorrect responses to Tones 1 and 4 appear to be random. As shown by all six tables, low-pass filtering did not appear to affect the accuracy of the responses. Figure 3-3 shows the mean correct out of 21 for each tone in each noise condition. Figure 3-4 shows the percent correct for each tone in both quiet conditions, unfiltered (QU) and filtered (QF).

An analysis of variance was conducted to determine the significance of competing noise, tone, and filtering on the subjects' responses. It was found that there was a significant main effect of competing noise conditions (none, S:N = 0 dB, S/N = -4 dB) on the total number of correct responses ($F(2,18) = 247.17$, $p < .01$). Also significant was the main effect of tone ($F(3,27) = 77.40$, $p < .01$). As well, there was a significant interaction between tone and competing noise ($F(6,54) = 42.13$, $p < .01$). It was found that whether or not there was filtering had no significant effect on the number of "correct" responses.

A Student-Newman-Keuls test of multiple comparisons demonstrated that in the quiet conditions, subjects gave significantly more "correct" responses than in the 0 dB S:N conditions, and that in the 0 dB S:N conditions, subjects gave significantly more "correct" responses than in the -4 dB S:N conditions (M = 20.80, 15.94, and 10.97 respectively, out of a possible total of 21).

A Student-Newman-Keuls test of multiple comparisons demonstrated that across all test conditions, there was no significant difference between the number of "correct" responses to Tone 1 and Tone 4 (M = 18.19 and 18.52 respectively, out of a total 21). Subjects had significantly less "correct" responses to Tone 2 (M = 14.21) than to Tone 1 and 4, and Tone 3 provided significantly fewer "correct" responses than Tone 2 (M = 12.70).

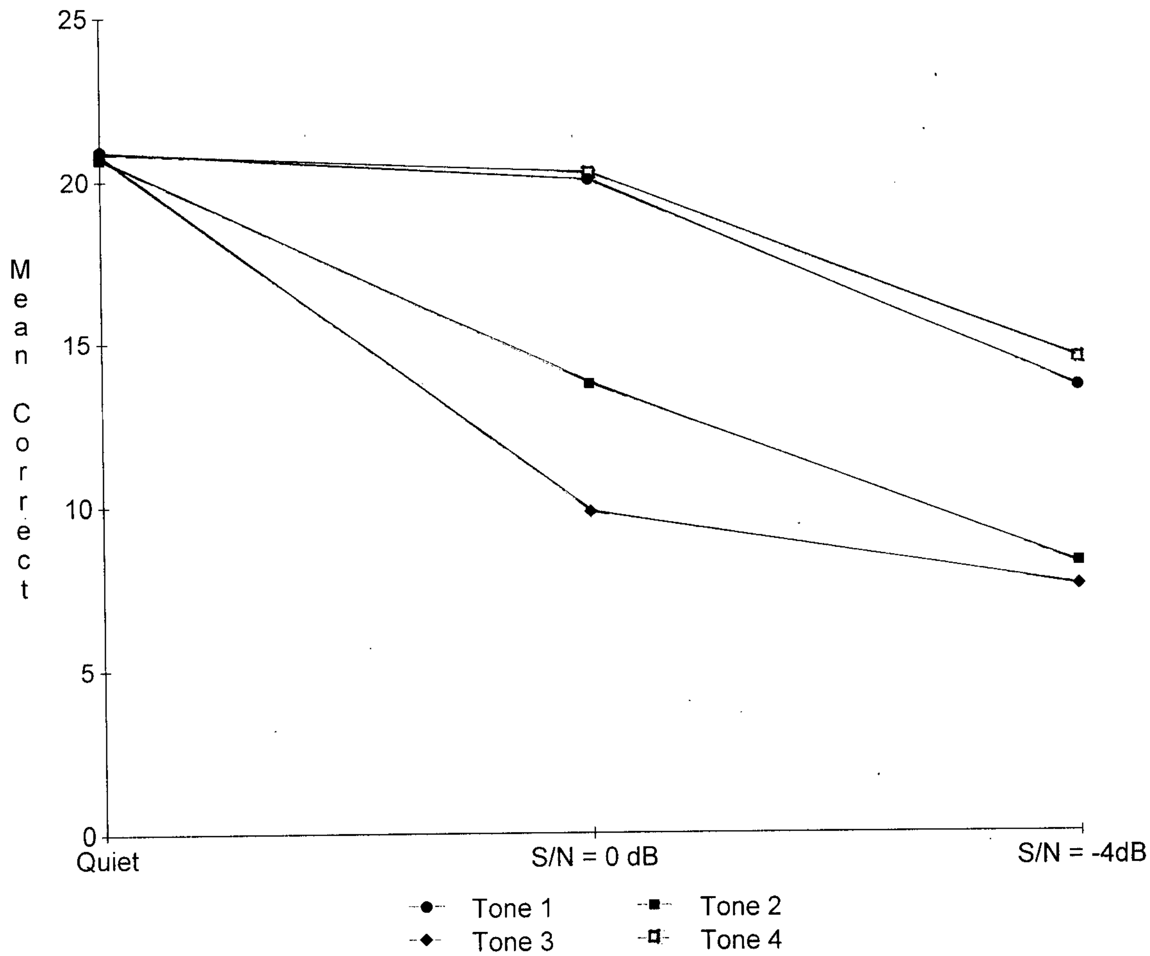

Figure 3-3. Mean correct out of 21 for each tone in each noise condition.

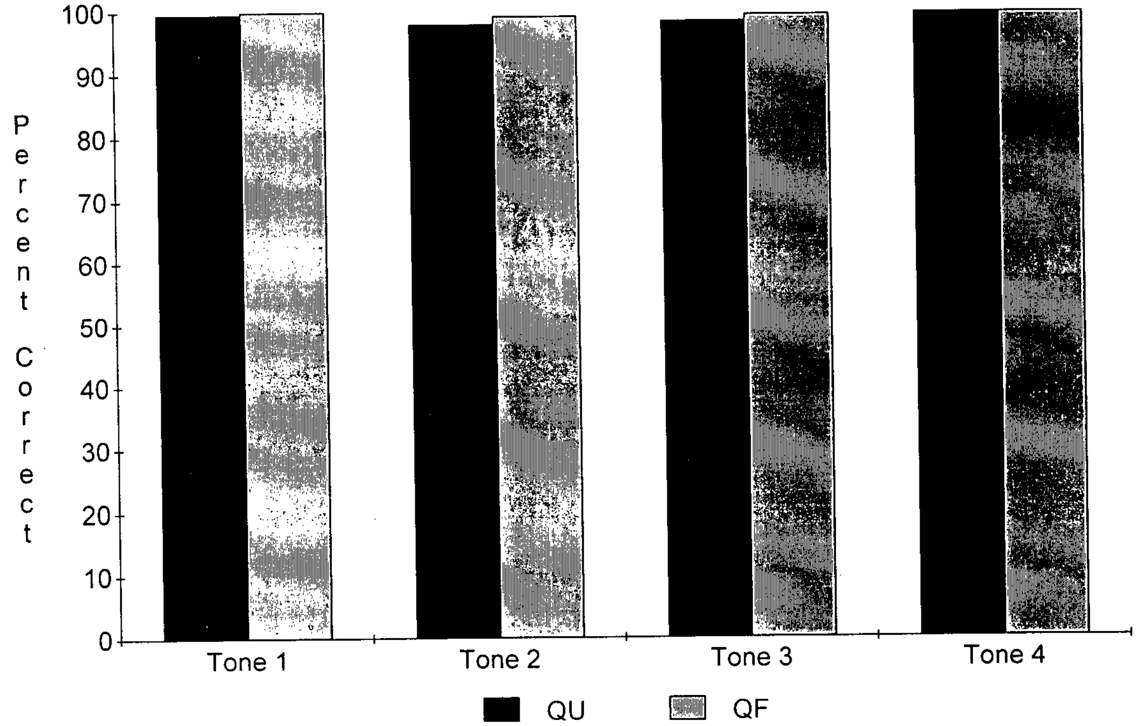

Figure 3-4. Percent correct for each tone in conditions Quiet, Unfiltered (QU) and Quiet, Filtered (QF).

In a third Student-Newman-Keuls test of multiple comparisons, it was demonstrated that in the quiet conditions, there were no significant differences in the number of "correct" responses to each tone; means ranged from 20.67 to 20.93 out of a possible total of 21 (see Figure 3-7.). However, in the 0 dB S:N conditions, subjects gave significantly more "correct" responses to Tone 1 and 4 (M = 20.02 and 20.22 respectively, out of 21) than to Tone 2 (M = 13.70), and they gave significantly more "correct" responses to Tone 2 than to Tone 3 (M = 9.82). In the -4 dB S:N conditions, again subjects gave more "correct" responses to Tone 1 and 4 (M = 13.62 and 14.47 respectively) than to Tone 2 (M = 8.25), and more "correct" responses to Tone 2 than to Tone 3 (M = 7.55).

4. DISCUSSION

4.1 Review of Hypotheses

The present study examined how the perception of Mandarin tones and Mandarin initial consonants are affected by competing background noise and low-pass filtering.

The following hypotheses were tested:

1) low-pass filtering will not affect the perception of tone in Mandarin;

2) competing white noise will not affect the perception of tone as greatly as it affects the perception of consonants in Mandarin;

3) the perception of aspiration and nasality cues in Mandarin will be superior to the perception of place of articulation and 'stop' cues in the presence of competing white noise and low-pass filtering.

4) competing white noise will cause more perceptual confusions among consonants in Mandarin than in English; and

5) the degree of consonantal and tonal confusion in Mandarin will vary with tone.

4.2 Summary of Results

4.2.1 Tone Perception in Mandarin

When there is no background noise and no filtering, listeners perceive all four tones nearly perfectly. The present study demonstrates that low-pass filtering has no significant effect on the perception of tone in Mandarin, supporting the first hypothesis. Competing white noise does have a significant effect on the perception of tone. Across all test conditions, listeners on average are more able to correctly perceive Tone 1 and Tone 4 than Tone 2 and Tone 3. As listening conditions worsen from quiet to -4 dB S:N, listeners' perception of all four tones declines. When competing white noise is introduced (S:N = 0 dB, S:N = -4 dB), listeners are more able to correctly perceive Tone 1 and 4 than Tone 2 and Tone 3.

4.2.2 Consonant Perception in Mandarin

The present study demonstrates that low-pass filtering, the level of competing white noise and the tone which is presented all significantly affect the perception of Mandarin initial consonants, supporting the last hypothesis. When there is low-pass filtering, there is a significant negative effect on the perception of Mandarin initial consonants. Listeners are more able to correctly perceive initial consonants in the quiet conditions, and as background noise is introduced and the listening condition worsens (S:N = +26 dB, S:N = +22 dB) the perception of initial consonants also worsens. Importantly, listeners are more able to correctly perceive initial consonants when the syllable is produced with Tone 4 than when the syllable is produced with Tone 1 or Tone 2. When the syllable is produced with Tone 3, listeners have the most trouble correctly perceiving the initial consonant.

4.3 Low-Pass Filtering and its Effect on the Perception of Tone

It was hypothesized that low-pass filtering would have no effect on the perception of tone in Mandarin, as tone is mainly perceived as change in the fundamental frequency (Howie,1976). Because the fundamental frequency of the human voice may range from 80 to 400 Hz (Ladefoged, 1982) and the effect of the low-pass filter used in the present study on this range of frequencies is negligible, low-pass filtering should not affect a listener's ability to perceive the fundamental frequency. Indeed, the present study demonstrated that low-pass filtering has no significant effect on the perception of Mandarin tone.

4.4 Competing White Noise: Its Effects on the Perception of Tone and Consonants

Hypothesis two was that the perception of tone would not be as greatly affected by competing white noise as would the perception of initial consonants. If the competing noise is viewed as a kind of "low-pass filter" that more effectively masks the relatively weak high-frequency components of speech than the relatively strong lower-frequency components of speech, (Miller & Nicely, 1955), it is logical to assume that the fundamental frequency which is the primary cue for tone perception will be masked less efficiently by the competing noise than the relatively higher-frequency consonants.

In the present study, it was found that in order to provide a listening environment with competing noise that proved to be somewhat difficult but not too taxing, the S:N for the tone perception experiments had to set to 0 dB. The average score in percent was 77.4 % for this condition with no filtering. In contrast, for the consonant experiments, the S:N ratio had to be set as high as +26 dB for the average score to be 72.4 %, otherwise the listeners scored very poorly. A reduction of 4 dB S:N from the easy noise condition to achieve a difficult noise condition resulted in the average score for tones dropping to 51.2 % while the average score for consonants dropped to 63.7 %. Thus, while the level of competing noise must be very high to begin to interfere with the perception of tone, further increases in noise result in marked reductions in tone perception. Relatively low levels of competing noise interfere with consonant perception, but further increases in the level of competing noise cause less of an incremental drop in consonant perception than in tone perception.

It is therefore apparent that competing noise does affect the perception of Mandarin consonants much more than it affects the perception of Mandarin tones. The S:N conditions corresponding to the easy listening situations for the perception of Mandarin initial consonants were surprisingly high, requiring that only a low intensity of background noise be present to significantly decrease the ability of a Mandarin listener to "correctly" perceive initial consonants. Perhaps this is due to the relatively high number of voiceless, high frequency consonants that occur in the Mandarin language, as discussed in section 1.4.2., which would be easily masked by background noise.

4.5 Perceptual Confusions Among Consonants in Mandarin vs English

Hypothesis four was that competing noise would cause more perceptual confusions among consonants in Mandarin than in English. As stated above, only a low intensity of background noise (S/N = +26 dB and S/N = +22 dB) was needed to significantly reduce the correct perception of consonants in Mandarin. For the correct perception of English consonants to be reduced to the same extent as was the perception of Mandarin consonants in the present study, S:N conditions had to be set as low as 0 dB in English (Miller & Nicely, 1955).

In other words, for the perception of English initial consonants, it takes more background noise to produce the same degree of consonantal confusion as was found for Mandarin. This appears to support the hypothesis that competing noise causes more consonantal confusions in Mandarin than in English. In Miller & Nicely's (1955) study, however, subjects were only asked to choose between 16 of the 21 English initial consonants, while in the present study, subjects were asked to choose between all 21 Mandarin initial consonants (without considering /w/ and /j/ as initial consonants). This may account for the increased difficulty that Mandarin listeners demonstrated in perceiving consonants in background noise; they had more consonants to choose from and therefore more confusions were possible. As well, the phonetic inventories of Mandarin and English differ in that Mandarin has four more voiceless affricates than English, whereas English has four voiced fricatives that Mandarin does not have (see Tables 4-1 and 4-2). Both languages have 21 initial consonants; English has four more voiced initial consonants than Mandarin, and Mandarin has four more voiceless initial consonants than English. Because voiceless consonants are more easily masked by background noise than are voiced consonants, given the higher inventory of voiceless

Table 4-1. Mandarin Initial Consonants

		Bilabial	Labiodental	Dental	Alveolar	Retroflex	Alveopalatal	Palatal	Velar	Glottal
Stop	aspirated	p^h			t^h				k^h	
	unaspirated	p			t				k	
Affricate	aspirated				ts^h	tʂ^h		tɕ^h		
	unaspirated				ts	tʂ		tɕ		
Fricative	voiceless		f		s	ʂ		ɕ	X	
	voiced									
Nasal	voiced	m			n					
Approximant	voiced				l	ɹ		j	w	

Table 4-2. English Initial Consonants

		Bilabial	Labiodental	Dental	Alveolar	Retroflex	Alveopalatal	Palatal	Velar	Glottal
Stop	voiceless	p			t				k	
	voiced	b			d				g	
Affricate	voiceless						t			
	voiced						d			
Fricative	voiceless		f	θ	s		ʃ			h
	voiced		v	ð	z		ʒ			
Nasal	voiced	m			n					
Approximant	voiced				l, ɹ			j	w	

consonants in Mandarin, it follows that background noise would cause more consonantal confusions in Mandarin than in English.

Due to the fact that low-pass filtering and competing noise have been shown to have very similar effects on the types of consonantal confusions that occur during the perception of consonants (Miller & Nicely, 1955), it would be expected that since competing noise causes more consonantal confusions in Mandarin than in English, low-pass filtering would therefore also cause more consonantal confusions in Mandarin than in English. Again, one can view the higher number of voiceless, high- frequency phonemes present in Mandarin as compared to English as a possible reason for the stronger effect of competing noise on the perception of Mandarin consonants. This argument can also be used in hypothesizing that low-pass filtering would have a greater negative effect on the perception of Mandarin consonants than on the perception of English consonants.

To explore the nature of the confusions that arose, in the present study the perceptual confusions among Mandarin consonants were summarized by classifying the consonants in terms of distinctive features, as did Miller & Nicely (1955) in their study on the perceptual confusions among English consonants (see section 1.3). The Mandarin consonants were classified based on four features:

1) *Nasality* - refers to whether or not pressure is released through the nose by lowering the soft palate (/m,n/ versus all other consonants),

2) *Aspiration* - refers to whether or not voicing is delayed following the release of the stop (eg. /pʰ/ vs /p/),

3) *Place of Articulation* - refers to the location(s) of the vocal tract involved in the production of a sound, and

4) *Affrication, or the 'Stop' feature* - refers to whether or not the articulators close completely during articulation (eg. /t/ vs /s/).

Voicing was not included in the features used to classify the Mandarin consonants, unlike in the study by Miller and Nicely (1955), because voicing is not phonologically distinctive in Mandarin as it is in English. Aspiration in Mandarin is comparable to voicing in English, insofar as in Mandarin aspiration is phonologically distinctive, while voicing is phonologically distinctive in English.

In support of hypothesis three, it was found that competing white noise and low-pass filtering have similar effects on consonant perception in Mandarin, and that both with competing noise and low-pass filtering, the perception of nasality and aspiration cues are superior to the perception of stop cues and especially place of articulation cues. This is compatible with the results obtained by Miller & Nicely (1955) in English. In the present study, in the quiet, unfiltered condition, it was found that 99.9 % of nasality information was correctly recognized, 97 % of aspiration and stop information was correctly recognized, and 92 % of place of articulation information was correctly recognized. Low-pass filtering, and competing white noise at +22 dB S:N resulted in approximately 99 % of nasality information and 95 % of aspiration information still being correctly recognized, but only 87.5 % of stop information and 77.5 % of place of articulation information being correctly recognized.

4.6 Consonantal Confusion as it Varies with Tone

It was hypothesized that the degree of consonantal confusion in Mandarin would vary with tone. This hypothesis was based on the fact the syllables presented with the four tones in the present study had different average intensities (see Appendix A). Syllables produced with Tone 4 were of the highest intensity, and in order of decreasing intensity were syllables produced with Tone 1, Tone 2 and Tone 3. As stated in section 4.2.2, consonants presented in syllables produced with Tone 4 were the most often correctly perceived, followed by consonants produced with Tone 1 or 2, followed by consonants produced with Tone 3. This finding is more understandable if one takes into account the average intensities of the four tones. If a consonant is presented at a higher intensity than another, then the more intense consonant will remain audible until a higher noise level is reached.

4.7 Perception of the Four Mandarin Tones

As stated above in section 4.2.1, across all test conditions listeners on average are more able to "correctly" perceive Tone 1 and Tone 4 than Tone 2 and Tone 3. When confusions occur, they first occur between Tone 2 and Tone 3. At 0 dB S:N, an average of 91.5 % of the total errors occur in response to Tone 2 and 3, and 61.2 % of the total errors involve confusing Tone 2 for Tone 3 and vice versa. Only 8.5 % of the errors occur in response to Tone 1 and Tone 4. As the listening condition becomes more difficult, more errors in response to Tone 1 and Tone 4 occur. At -4 dB S:N, an average of 34.4 % of the total errors now occur in response to Tone 1 and Tone 4, and 65.7 % of the total errors occur in response to Tone 2 and Tone 3. However, unlike errors to tones 2 and 3 which tend to be confused with each other, when errors occur to tones 1 and 4, the error pattern is random.

Of the errors involved in tone perception in Mandarin, it has been extensively reported that most involve confusions between Tone 2 and Tone 3 (Gandour, 1978). Gandour (1978) suggests that this may be due to the similar physical characteristics of these tones, in that they both display rising glides and start at about the same pitch level. There is a phonological rule or *tone sandhi* rule in Mandarin in which a third-tone syllable followed by another third-tone syllable becomes a second-tone syllable (Li & Thompson, 1981). Perhaps the confusions between Tones 2 and 3 are due to both the phonetic similarities between Tones 2 and 3 and to the phonological instability of Tone 3.

The hypothesis that Tone 4 and Tone 3 should be maximally distinguishable because Tone 4 is shorter, and Tone 3 is longer than Tones 1 and 2 is obviously not supported by the data, as it is Tones 1 and 4 that are maximally distinguishable in the present study. As discussed in section 4.6, Tones 4 and 1 are more intense on average than Tones 2 and 3 in the present study, and this may account for the higher number of correct responses to Tones 1 and 4.

A study by Fox & James (1985) has demonstrated that the perception of tone in Mandarin can be significantly affected by the lexical status of the speech token. It would be interesting to determine if in the present study lexical status affected the perception of tone, and if perhaps this could account for the better performance in correctly perceiving Tone 1 and Tone 4. Sixty of the eighty-four stimuli in this study were actual words, while twenty-four were nonsense syllables. 86 % of the Tone 1 syllables were actual words and 71 % of the Tone 4 syllables were actual words, while only 62 % and 67 % of Tone 2 and Tone 3 syllables respectively were actual words. However, no information was found in the literature on the frequency of occurrence of the four tones in a representative sample of Mandarin discourse. This information could also be useful in investigating the difference in tone perception between the four tones.

4.8 Implications for the Hearing Impaired

As stated in Chapter 1, section 1.6.2, House (1990) discusses an hypothesis of tonal perception based on central processing theories and models of pitch perception. In response to evidence in the literature that suggests that hearing impaired listeners may have more difficulty using tonal movement cues for coding stress, intonation and tone, House (1990) suggests that the inability to process correctly the tonal movement in relationship to syllable and segment boundaries, as well as absolute threshold changes and reduced frequency and temporal resolution, may contribute to the decreased sensitivity to tonal movement perception. House (1990) suggests that hearing-impaired listeners may be able to use visual cues to align fundamental frequency information with segmental boundaries, as studies have demonstrated that comprehension is significantly enhanced when visual cues are supplemented with fundamental frequency information.

The present study has demonstrated that low-pass filtering, or in effect a change in absolute thresholds, does not greatly affect a listener's ability to perceive tone in isolated Mandarin syllables. Although the present study was designed to test consonantal and tonal perception of normal-hearing listeners, low-pass filtering was introduced in order to provide one of the characteristics of a high-frequency sensorineural hearing loss, that of elevated absolute thresholds. The study can therefore not capture a hearing-impaired listener's difficulties in perceiving tonal movement due to such characteristics as reduced frequency and temporal resolution.

The present study suggests that the perception of consonants in Mandarin is more affected by competing noise and low-pass filtering than is the perception of consonants in English. This leads to the conclusion that a hearing-impaired speaker/listener of Mandarin needs a much better listening environment and therefore much less background noise than a hearing-impaired speaker/listener of English for maximum intelligibility of consonants. However, results obtained for the present study suggest that hearing-impaired listeners may not have difficulty in perceiving tone in Mandarin, and thus have a definite advantage over English-speaking hearing-impaired listeners in that they are receiving added meaningful information. Tone is phonemic and therefore will provide cues and context from which a hearing-impaired listener can draw if other segmental phonemes such as consonants have been missed. It appears, then, that there is somewhat of a "trade-off" between reduced intelligibility of consonants in the presence of background noise and with low-pass filtering, and increased meaningful information provided by tone that an English-speaking hearing-impaired listener does not receive.

How can this information help the audiologist, care-giver and teacher to best help a Mandarin-speaking hearing-impaired individual? The number one priority would appear to be the reduction of background noise to provide the best possible listening environment. Although this is important for all hearing-impaired listeners, it appears to be absolutely essential for the Mandarin hearing-impaired listener in order to maximize intelligibility. An important area of aural rehabilitation, along with traditional strategies, would be the awareness and practise of how tone can provide cues to a hearing-impaired listener if he or she 'missed' a word. As a student clinician working at an Audiology Clinic in an area with a large Chinese population (both Mandarin and Cantonese), the present investigator noted that many parents of Chinese hearing-impaired children did not notice difficulties in their child's hearing until he or she began communicating in English at school and in the community. Rosa Abreu (1995) notes that children whose first language (such as Spanish) does not depend so much on high frequency phonemes for word understanding (as in English), typically present with good intelligibility and normal speech and language development in their native language. However, when these children must learn in English, difficulties arise. Abreu suggests that all children in "English-as-a-second-language" programs receive a complete audiological evaluation and that parents have a clear understanding of the effects of an ESL classroom on a hearing-impaired child.

4.9 Future Directions

The present study has investigated how the perception of tone and consonants in Mandarin for normal-hearing listeners is affected by competing white noise and low-pass filtering. As discussed earlier, although low-pass filtering can mimic the changes in absolute thresholds that characterize a high-frequency sensorineural hearing loss, such a study can not take into account such characteristics as reduced temporal and frequency resolution, which very likely can affect the perception of tone. The findings described in this study might guide future research that would investigate these same issues with hearing-impaired listeners.

Future research could examine tonal perception as it occurs in discourse, and not simply in citation form. An important phenomenon called *tone sandhi* occurs during discourse, in which tones change when syllables are put side by side. Therefore, a syllable may have a certain tone in isolation, but when followed by another syllable in discourse, this syllable may now carry a different tone without a change in meaning (Li & Thompson, 1981). Although the present study suggests that hearing-impaired listeners would not have problems with tone perception for syllables in isolation, tone perception in discourse may differ significantly.

A final idea for future research might involve investigating the perception of what is called the *neutral* tone in Mandarin. Besides the four main tones in Mandarin, if a syllable is unstressed or is weakly stressed, it loses its contrastive pitch and is described as having a neutral tone. Because suffixes and grammatical particles usually carry a neutral tone (Li & Thompson, 1981), it would be very interesting to know if hearing-impaired listeners have difficulty perceiving this neutral tone due its unstressed position, and how this would affect their overall understanding of the conversation.

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APPENDIX A
Intensity and Duration of Stimuli

Table A-1. Root Mean Square (RMS) in Volts of the Sound Pressure Level of the Stimuli

	Tone 1	Tone 2	Tone 3	Tone 4
ba	0.7457	0.6218	0.256	0.7309
ca	0.4972	0.3371	0.1794	0.544
cha	0.5772	0.3623	0.1704	0.4426
da	0.7756	0.5351	0.2768	0.9608
fa	0.9281	0.461	0.2452	0.6931
ga	0.5625	0.4797	0.2997	0.7771
ha	0.5649	0.5729	0.2327	0.5133
jia	0.5753	0.4753	0.2246	0.5027
ka	0.5201	0.4103	0.1555	0.6769
la	0.5413	0.5204	0.2967	0.998
ma	0.4141	0.309	0.1543	0.7314
na	0.3591	0.3908	0.2044	0.6763
pa	0.5641	0.4702	0.2145	0.7809
qia	0.5438	0.3621	0.1905	0.6343
ra	0.6337	0.5677	0.2369	0.627
sa	0.7017	0.3522	0.2104	0.6138
sha	0.4497	0.3702	0.233	0.5301
ta	0.6711	0.3442	0.2034	0.7991
xia	0.4857	0.4142	0.1787	0.5365
za	0.8191	0.6184	0.1705	0.9161
zha	0.6042	0.4617	0.2295	0.9516

Average root mean square (RMS) in Volts of the sound pressure level of all 84 stimuli: 0.490 Volts (absolute values ranging from 0.154 to 0.998 Volts).

Average RMS in Volts of the sound pressure level of the stimuli for Tones 1-4:

Tone 1: 0.597
Tone 2: 0.449
Tone 3: 0.217
Tone 4: 0.697

Table A-2. Duration in milliseconds of the stimuli.

	Tone 1	Tone 2	Tone 3	Tone 4
ba	370	440	568	299
ca	443	466	754	379
cha	443	526	667	392
da	331	376	568	318
fa	370	363	536	428
ga	344	414	581	318
ha	370	472	603	379
jia	402	408	640	347
ka	421	478	622	344
la	482	501	588	379
ma	405	545	661	405
na	431	434	606	376
pa	418	494	641	350
qia	453	498	590	382
ra	480	414	661	370
sa	490	436	687	360
sha	530	584	690	408
ta	405	494	723	376
xia	520	532	663	363
za	408	402	546	312
zha	373	450	539	327

Average duration of the 84 stimuli: 469 ms

Average duration of the stimuli for tones 1-4:

Tone 1: 423 ms
Tone 2: 463 ms
Tone 3: 625 ms
Tone 4: 362 ms

APPENDIX B
Instructions to the Participants

INSTRUCTIONS FOR CONSONANT WARM-UP

You are going to hear a series of one-syllable "words". These syllables may or may not be real Mandarin words. Each syllable that you hear will begin with one of 21 consonants.

Each time that you hear a syllable, use the mouse to move the cursor to the Pinyin symbol on the screen that matches the consonant that you heard. Click the left mouse button once. There will be 21 Pinyin symbols on the screen, one for each of the 21 consonants. If your response is correct, the box that you clicked on will flash orange and then green. If your response is incorrect, the box that you clicked on will flash orange and the corret box will flash red.

If you are not sure which consonant you heard, GUESS! The next syllable will not be played until you have clicked on one of the 21 boxes.

GOOD LUCK!

INSTRUCTIONS FOR CONSONANT EXPERIMENT, QUIET, UNFILTERED

You are going to hear a series of one-syllable "words". These syllables may or may not be real Mandarin words. Each syllable that you hear will begin with one of 21 consonants.

Each time that you hear a syllable, use the mouse to move the cursor to the Pinyin symbol on the screen that matches the consonant that you heard. Click the left mouse button once. There will be 21 Pinyin symbols on the screen, one for each of the 21 consonants. The symbol that you clicked on will flash orange.

If you are not sure which consonant you heard, GUESS! The next syllable will not be played until you have clicked on one of the 21 boxes.

GOOD LUCK!

INSTRUCTIONS FOR CONSONANT EXPERIMENT, QUIET, FILTERED

You are going to hear a series of one-syllable "words". Again, these syllables may or may not be real Mandarin words. Each syllable that you hear will begin with one of 21 consonants.

In this condition, the syllables will be filtered so that some of the speech sounds are taken out. The speech is filtered to simulate a hearing loss.

Each time that you hear a syllable, use the mouse to move the cursor to the Pinyin symbol on the screen that matches the consonant that you heard. Click the left mouse button once. There will be 21 Pinyin symbols on the screen, one for each of the 21 consonants. The symbol that you clicked on will flash orange.

If you are not sure which consonant you heard, GUESS! The next syllable will not be played until you have clicked on one of the 21 boxes.

GOOD LUCK!

INSTRUCTIONS FOR CONSONANT EXPERIMENT WITH NOISE, UNFILTERED

You are going to hear a series of one-syllable "words". These syllables may or may not be real Mandarin words. Each syllable that you hear will begin with one of 21 consonants.

As you listen to the syllables, you will hear static-like noise in the background. Try to ignore the noise and listen for the syllables.

Each time that you hear a syllable, use the mouse to move the cursor to the Pinyin symbol on the screen that matches the consonant that you heard. Click the left mouse button once. There will be 21 Pinyin symbols on the screen, one for each of the 21 consonants. The symbol that you clicked on will flash orange.

If you are not sure which consonant you heard, GUESS! The next syllable will not be played until you have clicked on one of the 21 boxes.

GOOD LUCK!

INSTRUCTIONS FOR CONSONANT EXPERIMENT WITH NOISE AND FILTERING

You are going to hear a series of one-syllable "words". Again, these syllables may or may not be real Mandarin words. Each syllable that you hear will begin with one of 21 consonants.

As you listen to the syllables, you will hear static-like noise in the background. Try to ignore the noise and listen for the syllables.

In this condition, the syllables will be filtered so that some of the speech sounds are taken out. The speech is filtered to simulate a hearing loss.

Each time that you hear a syllable, use the mouse to move the cursor to the Pinyin symbol on the screen that matches the consonant that you heard. Click the left mouse button once. There will be 21 Pinyin symbols on the screen, one for each of the 21 consonants. The symbol that you clicked on will flash orange.

If you are not sure which consonant you heard, GUESS! The next syllable will not be played until you have clicked on one of the 21 boxes.

GOOD LUCK!

INSTRUCTIONS FOR TONE WARM-UP

You are going to hear a series of one-syllable "words". These syllables may or may not be real Mandarin words. Each syllable that you hear will carry one of four tones: tone 1, tone 2, tone 3, or tone 4.

Each time that you hear a syllable, use the mouse to move the cursor to the box on the screen that matches the tone that you heard. Click the left mouse button once. There will be four boxes on the screen, one for each of the four tones. If your response is correct, the box that you clicked on will flash orange and then green. If your response is incorrect, the box that you clicked on will flash orange and the correct box will flash red.

If you are not sure which tone you heard, GUESS! The next syllable will not be played until you have clicked on one of the four boxes.

GOOD LUCK!

INSTRUCTIONS FOR TONE EXPERIMENT, QUIET, UNFILTERED

You are going to hear a series of one-syllable "words". These syllables may or may not be real Mandarin words. Each syllable that you hear will carry one of four tones: tone 1, tone 2, tone 3, or tone 4.

Each time that you hear a syllable, use the mouse to move the cursor to the box on the screen that matches the tone that you heard. Click the left mouse button once. There will be four boxes on the screen, one for each of the four tones. The box that you clicked on will flash orange.

If you are not sure which tone you heard, GUESS! The next syllable will not be played until you have clicked on one of the four boxes.

GOOD LUCK!

INSTRUCTIONS FOR TONE EXPERIMENT, QUIET, FILTERED

You are going to hear a series of one-syllable "words". These syllables may or may not be real Mandarin words. Each syllable that you hear will carry one of four tones: tone 1, tone 2, tone 3, or tone 4.

In this condition, the syllables will be filtered so that some of the speech sounds are taken out. The speech is filtered to simulate a hearing loss.

Each time that you hear a syllable, use the mouse to move the cursor to the box on the screen that matches the tone that you heard. Click the left mouse button once. There will be four boxes on the screen, one for each of the four tones. The box that you clicked on will flash orange.

If you are not sure which tone you heard, GUESS! The next syllable will not be played until you have clicked on one of the four boxes.

GOOD LUCK!

INSTRUCTIONS FOR TONE EXPERIMENT WITH NOISE, UNFILTERED

You are going to hear a series of one-syllable "words". These syllables may or may not be real Mandarin words. Each syllable that you hear will carry one of four tones: tone 1, tone 2, tone 3, or tone 4.

As you listen to the syllables, you will hear static-like noise in the background. Try to ignore the noise and listen for the syllables.

Each time that you hear a syllable, use the mouse to move the cursor to the box on the screen that matches the tone that you heard. Click the left mouse button once. There will be four boxes on the screen, one for each of the four tones. The box that you clicked on will flash orange.

If you are not sure which tone you heard, GUESS! The next syllable will not be played until you have clicked on one of the four boxes.

GOOD LUCK!

INSTRUCTIONS FOR TONE EXPERIMENT WITH NOISE AND FILTERING

You are going to hear a series of one-syllable "words". These syllables may or may not be real Mandarin words. Each syllable that you hear will carry one of four tones: tone 1, tone 2, tone 3, or tone 4.

As you listen to the syllables, you will hear static-like noise in the background. Try to ignore the noise and listen for the syllables.

In this condition, the syllables will be filtered so that some of the speech sounds are taken out. The speech is filtered to simulate a hearing loss.

Each time that you hear a syllable, use the mouse to move the cursor to the box on the screen that matches the tone that you heard. Click the left mouse button once. There will be four boxes on the screen, one for each of the four tones. The box that you clicked on will flash orange.

If you are not sure which tone you heard, GUESS! The next syllable will not be played until you have clicked on one of the four boxes.

GOOD LUCK!

APPENDIX C
Consonant Perception Results, All Subjects, For Tones 1-4

Table C-1. Confusion Matrix for Condition: S/N = +26 dB, Low-Pass Filtering, All Subjects, Tone 1

	b	c	ch	d	f	g	h	ji	k	l	m	n	p	qi	r	s	sh	t	xi	z	zh
b	8				19								1				2				
c		9	1				3		2				6					9			
ch		5	3				1		1				2					18			
d	3			21	2	2										2					
f					24	1			1							2				2	
g				2	5	8			1							6	3			2	3
h		4	2		2		5		5				4					8			
ji								23											7		
k		6	1				4		2				4					13			
l										30											
m										5	25										
n										3	9	18									
p		1							1				8					20			
qi														29			1				
r							1	1		8					19				1		
s									1							12	7			8	2
sh			4		2									3		6	14				1
t		4	1						2				4					19			
xi								18						2					9	1	
z					1	3										9	2			9	6
zh					1										1	10	7		1	6	4

Percentage Correct: 47.4603 %

Table C-2. Confusion Matrix for Condition: S/N = +26 dB, Low-Pass Filtering, All Subjects, Tone 2

	b	c	ch	d	f	g	h	ji	k	l	m	n	p	qi	r	s	sh	t	xi	z	zh
b	28			1	1																
c		6	6				2		2				8				1	5			
ch		7	10						2				6					5			
d				24	1															5	
f	12			4	5	3			1				1			1	1			2	
g				4		6											5			13	2
h		1	2				15		1				9					2			
ji								11											19		
k		7	2				1		5				10					5			
l										16					14						
m										1	16	13									
n												29			1						
p	1	3					1						21					4			
qi														26			2			1	1
r										1					28						1
s													1			4	7			12	6
sh					1											8	17			2	2
t		1	4				6		2				11			1		5			
xi								14						1					15		
z				1									1			4	7			14	3
zh						1											5			10	14

Percentage Correct: 50.0 %

Table C-3. Confusion Matrix for Condition: S/N = +26 dB, Low-Pass Filtering, All Subjects, <u>Tone 3</u>

	b	c	ch	d	f	g	h	ji	k	l	m	n	p	qi	r	s	sh	t	xi	z	zh
b	16			5	5	1							2				1				
c		1	2				1		7									19			
ch		2	5				1		9				1					11		1	
d	1			15		2										4	4			2	2
f	10			2	12	4							1				1				
g				9		8			1							2	3			3	4
h							5		10				2					13			
ji								30													
k		3	2						11			1	1					12			
l										25		1			4						
m											25	5									
n								1			1	26		1	1						
p							1		13				3					13			
qi								1						24			5				
r										1					19		4				6
s				8		1										1	7			7	6
sh				1					1								16			2	10
t		1	1				1		7				2					18			
xi								29										1			
z								7									9		2	2	10
zh						2										2	10			10	6

Percentage Correct: 42.5397 %

Table C-4. Confusion Matrix for Condition: S/N = +26 dB, Low-Pass Filtering, All Subjects, <u>Tone 4</u>

	b	c	ch	d	f	g	h	ji	k	l	m	n	p	qi	r	s	sh	t	xi	z	zh
b	23			4	3																
c		2	3						1				15					9			
ch		4	5		1		1		2				12			1		4			
d				29																	1
f	3			1	26																
g	2			19	1	8															
h		2	2				8	1	5				9					3			
ji								13						1					16		
k		3	3	1			3		6				5					9			
l										18	1	7			4						
m											24	6									
n										2		28									
p		3	1						1				16					9			
qi														28					2		
r										1					28						1
s		1			1											10	9			7	2
sh			1											1		4	21		1	2	
t		3	2				1		3				8					13			
xi								3						3					24		
z		1				3										7	1			10	8
zh						1			1							4	9		1	7	7

Percentage Correct: 55.0794 %

Table C-5. Confusion Matrix for Condition: S/N = +26 dB, Unfiltered, All Subjects, Tone 1

	b	c	ch	d	f	g	h	ji	k	l	m	n	p	qi	r	s	sh	t	xi	z	zh
b	15				14					1											
c		5					1		1				1					22			
ch		3	27																		
d				30																	
f					30																
g						19										2				3	6
h		2	1				9		2				2					14			
ji								26						1					3		
k		2					1		8				3					16			
l										29					1						
m											30										
n												30									
p		1					1					1	20					7			
qi														29					1		
r										2					28						
s																8	4			15	3
sh																3	27				
t		1					1						1					27			
xi								23											7		
z																3				24	3
zh																				5	25

Percentage Correct: 71.9048 %

Table C-6. Confusion Matrix for Condition: S/N = +26 dB, Unfiltered, All Subjects, Tone 2

	b	c	ch	d	f	g	h	ji	k	l	m	n	p	qi	r	s	sh	t	xi	z	zh
b	26				4																
c		6	5						1				4					14			
ch			29														1				
d	1			27																	2
f	15			1	14																
g				3		9											1			17	
h		2	1				5		3				16					3			
ji								23											7		
k		2	1						17				5					5			
l										27					3						
m											26	4									
n												30									
p		1											26					3			
qi								1						28					1		
r										1					29						
s																2	1			21	6
sh																	30				
t		2	1				1		2				10					14			
xi								19											11		
z				1																27	2
zh																				3	27

Percentage Correct: 68.7302 %

Table C-7. Confusion Matrix for Condition: S/N = +26 dB, Unfiltered, All Subjects, Tone 3

	b	c	ch	d	f	g	h	ji	k	l	m	n	p	qi	r	s	sh	t	xi	z	zh
b	24				6																
c		5	3										1			1		20			
ch		4	26																		
d				22												4				4	
f	11			1	17											1					
g				2		27			1												
h							8		7				2					13			
ji								27											3		
k			2						20									7		1	
l										29		1									
m											30										
n				1								29									
p													20					10			
qi								1						29							
r						1				2					20		1			6	
s				5		1										9	3			12	
sh																1	29				
t		2							2									26			
xi								29						1							
z																1	5			11	13
zh															1					5	24

Percentage Correct: 68.5714 %

Table C-8. Confusion Matrix for Condition: S/N = +26 dB, Unfiltered, All Subjects, <u>Tone 4</u>

	b	c	ch	d	f	g	h	ji	k	l	m	n	p	qi	r	s	sh	t	xi	z	zh
b	27			1	1								1								
c		2	1										5		1			21			
ch		1	28										1								
d				30																	
f	3				27																
g				4		24			1		1										
h							13					1	13					3			
ji								23						1					6		
k									28				1					1			
l										28		1			1						
m											30										
n												30									
p													28					2			
qi														30							
r										1					29						
s																14	3			12	1
sh																	30				
t													8			1	1	20			
xi								14											16		
z																6	1			22	1
zh																				3	27

Percentage Correct: 80.3175 %

Table C-9. Confusion Matrix for Condition: S/N = +22 dB, Low-Pass Filtering, All Subjects, Tone 1

	b	c	ch	d	f	g	h	ji	k	l	m	n	p	qi	r	s	sh	t	xi	z	zh
b	5			2	22	1															
c		4	4			1			5				2					14			
ch		4	4						4				2				1	15			
d	2			25	1															1	1
f				1	23								1			3	1			1	
g			2	3	2	2			1							11	5	2			2
h		4	1				2	1	1				3					18			
ji								17						2	1				10		
k		4	1				1		1				5					18			
l										29					1						
m										6	24										
n						1				13	6	7			3						
p		1	1				1						7					20			
qi			2					2						23			1		1		1
r								2		9					17		1		1		
s																13	5	1		6	5
sh					3									3		8	10			1	5
t		6	4				1		3				4					12			
xi								17						1			1		11		
z	1				2	1										10	4	1		7	4
zh					2											4	11		1	5	7

Percentage Correct: 39.6825 %

Table C-10 Confusion Matrix for Condition: S/N = +22 dB, Low-Pass Filtering, All Subjects, Tone 2

	b	c	ch	d	f	g	h	ji	k	l	m	n	p	qi	r	s	sh	t	xi	z	zh
b	27			1	1			1													
c		4	9				1		2				9					5			
ch		4	14						3				4					5			
d				20												1	1			6	2
f	15			1	7	4										1	1			1	
g		1		3	2	3										2	3			13	3
h		1	4				9		3				11					2			
ji								13						1					16		
k		3	5				1		7				8					5	1		
l										16		2			12						
m								1		2	12	15									
n										1		28			1						
p		1	1		1				3				13					11			
qi								1					1	21			5		1	1	
r										1					28					1	
s						1											6	1		13	9
sh																4	11			10	5
t		3	4				1		5				10					7			
xi								15											15		
z				2						1						6	8			7	6
zh				1								1					11			8	9

Percentage Correct: 43.0159 %

Table C-11. Confusion Matrix for Condition: S/N = +22 dB, Low-Pass Filtering, All Subjects, Tone 3

	b	c	ch	d	f	g	h	ji	k	l	m	n	p	qi	r	s	sh	t	xi	z	zh
b	16			5	5	1											2	1			
c		1	1						10				3					15			
ch	2	1	5		1		1		8		1		2				1	8			
d			1	9												5	3	1		4	7
f	10			5	12	2											1				
g				9		3						1				3	6			4	4
h		3	2		1		3		7				3					11			
ji								28											2		
k		3	7				1		10									9			
l								1		27		1			1						
m										2	15	13									
n								4		2		24									
p		2	1	1					11					1				14			
qi								1						22		1	5		1		
r						1		1							5		5			5	13
s				11		1										1	5			9	3
sh								1								4	11			3	11
t		1	3						10				1				1	14			
xi								29			1										
z						1		5									8				16
zh						3										6	7			5	9

Percentage Correct: 34.127 %

Table C-12. Confusion Matrix for Condition: S/N = +22 dB, Low-Pass Filtering, All Subjects, Tone 4

	b	c	ch	d	f	g	h	ji	k	l	m	n	p	qi	r	s	sh	t	xi	z	zh
b	22			6	2																
c		1	5				1		4				15				1	3			
ch		6	6				1		2				9					6			
d				30																	
f	9				21																
g	4			19		3		1					1							1	1
h		1	2				5		3				14					5			
ji								6						4					20		
k		1	3				4		5				11					6			
l				2						19		7			2						
m											18	11		1							
n												30									
p		1	4				1		1	1			15			1		6			
qi								1						19		2	5		2		1
r										2					28						
s					1											13	11			3	2
sh		1							1							4	23				1
t		2	4				1		2				11	1			1	8			
xi								3						3					24		
z					1	1										6	8	1		8	5
zh					2									2		1	15		1	4	5

Percentage Correct: 49.0476 %

Table C-13. Confusion Matrix for Condition: S/N = +22 dB, Unfiltered, All Subjects, <u>Tone 1</u>

	b	c	ch	d	f	g	h	ji	k	l	m	n	p	qi	r	s	sh	t	xi	z	zh
b	7				22	1															
c		1					1		1			1	3					23			
ch		3	27																		
d				28	1													1			
f	1				29																
g						13			1							2	2			8	4
h		2					6		1			1	4					16			
ji						1		21											8		
k		1					1		3				4					21			
l										29					1						
m											29	1									
n												30									
p							3						12					15			
qi			1											27					2		
r										3					25					2	
s																6	3			13	8
sh																1	29				
t							2						4					24			
xi								20											10		
z																6	1			19	4
zh																2	1			9	18

Percentage Correct: 62.381 %

Table C-14. Confusion Matrix for Condition: S/N = +22 dB, Unfiltered, All Subjects, Tone 2

	b	c	ch	d	f	g	h	ji	k	l	m	n	p	qi	r	s	sh	t	xi	z	zh
b	29				1																
c		4	3						1				10					12			
ch		1	29																		
d				24													2	1		3	
f	11				17								2								
g				6		5														16	3
h		3	1				1		3				17					5			
ji								21						2					7		
k		2	2						10				8					8			
l										25					5						
m										2	17	11									
n												30									
p							1						26					3			
qi			1											29							
r										1				1	26					2	
s																				16	14
sh																1	29				
t		3											9					18			
xi								20						1					9		
z				2		1										1				22	4
zh																				2	28

Percentage Correct: 63.3333 %

Table C-15. Confusion Matrix for Condition: S/N = + 22 dB, Unfiltered, All Subjects, Tone 3

	b	c	ch	d	f	g	h	ji	k	l	m	n	p	qi	r	s	sh	t	xi	z	zh
b	21			1	8																
c		2	2						3				1					22			
ch		4	26																		
d				19				1								1	4			2	3
f	14			1	15																
g				3		20			2							1					4
h		2					3		7				1					17			
ji								28		1				1							
k		5	4						12									9			
l										28					2						
m											28	2									
n												30									
p			1										10					19			
qi								1						28			1				
r						1						1			11		4			7	6
s				9												1	3	1	2	6	8
sh														1			21				8
t		2							5				1					22			
xi								29											1		
z								1									5			8	16
zh																	2			9	19

Percentage Correct: 56.0317 %

Table C-16. Consonant Matrix for Condition: S/N = +22 dB, Unfiltered, All Subjects, Tone 4

	b	c	ch	d	f	g	h	ji	k	l	m	n	p	qi	r	s	sh	t	xi	z	zh
b	29				1																
c		1	1	1					2			2	6					17			
ch		2	26					1										1			
d				29																1	
f	2				27					1											
g				13		14			1												2
h		1					14		2				11					2			
ji								20											10		
k		2					1		19	1			4					3			
l										28		1			1						
m										1	27	2									
n									1			29									
p													21					9			
qi			1											28					1		
r										2					26					2	
s																10	2			15	3
sh																3	24				3
t							1		1				8					20			
xi								6						2					22		
z						2										7	2			18	1
zh																	1				29

Percentage Correct: 73.1746 %

Table C-17. Confusion Matrix for Condition: Quiet, Low-Pass Filtering, All Subjects, Tone 1

	b	c	ch	d	f	g	h	ji	k	l	m	n	p	qi	r	s	sh	t	xi	z	zh
b	27				2	1															
c		15	10										2					3			
ch		10	16															4			
d	1			26		1										1		1			
f					29												1				
g				1		23										1	2			2	1
h	1	6	1				11		1				3					7			
ji								24											6		
k		9							15				2					4			
l										29					1						
m											30										
n											4	26									
p													28					2			
qi		1				1								25					3		
r							1			3					26						
s		1														13	6			4	6
sh			1													3	22			1	3
t													3					27			
xi								1						1				1	27		
z																5	5			12	8
zh																2	2			10	16

Percentage Correct: 74.127 %

Table C-18. Confusion Matrix for Condition: Quiet, Low-Pass Filtering, All Subjects, Tone 2

	b	c	ch	d	f	g	h	ji	k	l	m	n	p	qi	r	s	sh	t	xi	z	zh
b	29				1																
c		13	13										3							1	
ch		2	18										2					8			
d				24	1												4	1			
f	20				9												1				
g				18		12															
h			1				20						9								
ji								21											9		
k		2	4						17				3					4			
l										25		2			3						
m										1	21	8									
n												30									
p													28					2			
qi	1		2											26					1		
r										1					27					2	
s																2	9			9	10
sh																	29			1	
t									1				11					18			
xi								5											25		
z																	5			18	7
zh																	6			2	22

Percentage Correct: 68.8889 %

Table C-19. Confusion Matrix for Condition: Quiet, Low-Pass Filtering, All Subjects, Tone 3

	b	c	ch	d	f	g	h	ji	k	l	m	n	p	qi	r	s	sh	t	xi	z	zh
b	27			3																	
c		9	14						1				1					5			
ch		4	22															4			
d				25													3	2			
f	11			1	17													1			
g				8		20											2				
h							14		1				9					6			
ji								28	1										1		
k		1	2						20				1					6			
l										30											
m											29	1									
n												30									
p									1				21					8			
qi			1											29							
r										3					25					1	1
s			1													6	12			5	6
sh																3	24		1	1	1
t									1				4					25			
xi								28											2		
z								2									5		1	5	17
zh																1	4			9	16

Percentage Correct: 67.3016 %

Table C-20. Confusion Matrix for Condition: Quiet, Low-Pass Filtering, All Subjects, <u>Tone 4</u>

	b	c	ch	d	f	g	h	ji	k	l	m	n	p	qi	r	s	sh	t	xi	z	zh
b	29				1																
c		13	9										5					3			
ch		5	22						1									2			
d				30																	
f					30																
g				7		22														1	
h			2				13						14					1			
ji								20											10		
k		4							19				2					5			
l										26		3			1						
m											30										
n												30									
p													29					1			
qi													1	29							
r										2					7						1
s			1													19	7			2	1
sh																1	29				
t													9					21			
xi								10						1					19		
z		1														6	2			14	7
zh																1	3			3	23

Percentage Correct: 78.4127 %

Table C-21. Confusion Matrix for Condition: Quiet, Unfiltered, All Subjects, Tone 1

	b	c	ch	d	f	g	h	ji	k	l	m	n	p	qi	r	s	sh	t	xi	z	zh
b	30																				
c		28	1														1				
ch		2	27														1				
d				29				1													
f					30																
g						30															
h							20		2				6					2			
ji								30													
k		1							29												
l										30											
m											30										
n												29			1						
p													30								
qi		1	1											27					1		
r										4					26						
s																28	2				
sh																	30				
t													4					26			
xi																			30		
z																	1			25	4
zh																				2	28

Percentage Correct: 93.9683 %

Table C-22. Confusion Matrix for Condition: Quiet, Unfiltered, All Subjects, <u>Tone 2</u>

	b	c	ch	d	f	g	h	ji	k	l	m	n	p	qi	r	s	sh	t	xi	z	zh
b	30																				
c		26	3																	1	
ch			30																		
d				30																	
f	19				11																
g				20		10															
h							14						16								
ji								30													
k		1							29												
l										27		1			2						
m											28	2									
n												30									
p													30								
qi		1	1											27					1		
r										1					29						
s																4	1			20	5
sh			1														29				
t									2				3					25			
xi														1					29		
z																				29	1
zh																				5	25

Percentage Correct: 82.8571 %

Table C-23. Confusion Matrix for Condition: Quiet, Unfiltered, All Subjects, Tone 3

	b	c	ch	d	f	g	h	ji	k	l	m	n	p	qi	r	s	sh	t	xi	z	zh
b	28			1					1												
c		23	7																		
ch			30																		
d				29														1			
f	2				28																
g						30															
h							11		2				17								
ji								30													
k		1							29												
l										27					3						
m											30										
n												30									
p	1												29								
qi		1												29							
r										3					26						1
s																24	6				
sh																	30				
t																		30			
xi								29						1							
z		1																		25	4
zh																				4	26

Percentage Correct: 86.3492 %

Table C-24. Confusion Matrix for Condition: Quiet, Unfiltered, All Subjects, Tone 4

	b	c	ch	d	f	g	h	ji	k	l	m	n	p	qi	r	s	sh	t	xi	z	zh
b	30																				
c		26	3																	1	
ch		2	28																		
d				30																	
f					30																
g				1		29															
h							17		5				8								
ji								30													
k									29				1								
l										29					1						
m											30										
n												30									
p													30								
qi			1											28					1		
r										2					28						
s																26	2			2	
sh																1	29				
t													10					20			
xi								27											3		
z																				28	2
zh																				2	28

Percentage Correct: 88.5714 %

APPENDIX D
Tone Perception Results for Individual Subjects

Subject 01:

Table D-1. Confusion Matrix for Condition: Quiet, Unfiltered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	63			
Tone 2		63		
Tone 3		4	59	
Tone 4				63

Table D-2. Confusion Matrix for Condition: Quiet, Filtered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	63			
Tone 2		63		
Tone 3			63	
Tone 4				63

Table D-3. Confusion Matrix for Condition: S/N = 0 dB, Unfiltered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	60	1	2	
Tone 2	2	43	16	2
Tone 3	10	24	27	2
Tone 4		1		62

Table D-4. Confusion Matrix for Condition: S/N = 0 dB, Filtered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	62		1	
Tone 2	2	44	16	1
Tone 3	14	24	24	1
Tone 4		1		62

Table D-5. Confusion Matrix for Condition: S/N = -4 dB, Unfiltered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	46	9	5	3
Tone 2	11	28	18	6
Tone 3	9	25	21	8
Tone 4	4	8	7	44

Table D-6. Confusion Matrix for Condition: S/N = -4 dB, Filtered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	49	7	4	3
Tone 2	11	25	21	6
Tone 3	9	28	22	44
Tone 4	1	7	8	47

Subject 02:

Table D-7. Confusion Matrix for Condition: Quiet, Unfiltered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	63			
Tone 2		62		1
Tone 3		1	62	
Tone 4			1	62

Table D-8. Confusion Matrix for Condition: Quiet, Filtered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	63			
Tone 2		63		
Tone 3			63	
Tone 4				63

Table D-9. Confusion Matrix for Condition: S/N = 0 dB, Unfiltered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	63			
Tone 2	9	40	9	5
Tone 3	27	15	17	4
Tone 4				63

Table D-10. Confusion Matrix for Condition: S/N = 0 dB, Filtered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	61	1	1	
Tone 2	9	39	11	4
Tone 3	19	11	25	8
Tone 4			1	62

Table D-11. Confusion Matrix for Condition: S/N = -4 dB, Unfiltered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	49	5	6	3
Tone 2	10	27	16	10
Tone 3	16	16	18	13
Tone 4	4	2	4	53

Table D-12. Confusion Matrix for Condition: S/N = -4 dB, Filtered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	47	9	4	3
Tone 2	17	25	13	8
Tone 3	19	14	22	8
Tone 4	4	1	4	54

Subject 03:

Table D-13. Confusion Matrix for Condition: Quiet, Unfiltered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	63			
Tone 2		62	1	
Tone 3			62	1
Tone 4			1	62

Table D-14. Confusion Matrix for Condition: Quiet, Filtered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	63			
Tone 2		63		
Tone 3		1	62	
Tone 4				63

Table D-15. Confusion Matrix for Condition: S/N = 0 dB, Unfiltered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	62		2	
Tone 2	3	39	19	2
Tone 3	8	20	30	5
Tone 4			1	62

Table D-16. Confusion Matrix for Condition: S/N = 0 dB, Filtered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	57	2	3	1
Tone 2	4	36	22	1
Tone 3	4	5	49	5
Tone 4				63

Table D-17. Confusion Matrix for Condition: S/N = -4 dB, Unfiltered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	50	6	6	1
Tone 2	3	28	27	5
Tone 3	9	10	40	4
Tone 4	4	3	7	49

Table D-18. Confusion Matrix for Condition: S/N = -4 dB, Filtered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	43	7	9	4
Tone 2	2	25	31	5
Tone 3	13	14	35	1
Tone 4	5	5	5	48

Subject 04:

Table D-19. Confusion Matrix for Condition: Quiet, Unfiltered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	63			
Tone 2		63		
Tone 3			63	
Tone 4				63

Table D-20. Confusion Matrix for Condition: Quiet, Filtered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	63			
Tone 2		63		
Tone 3			63	
Tone 4				63

Table D-21. Confusion Matrix for Condition: S/N = 0 dB, Unfiltered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	60	3		
Tone 2		43	18	2
Tone 3	6	10	46	1
Tone 4			1	62

Table D-22. Confusion Matrix for Condition: S/N = 0 dB, Filtered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	60	2	1	
Tone 2	2	42	18	1
Tone 3	3	15	42	3
Tone 4	1	2		60

Table D-23. Confusion Matrix for Condition: S/N = -4 dB, Unfiltered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	34	16	12	1
Tone 2	6	27	25	5
Tone 3	11	21	24	7
Tone 4	3	3	11	46

Table D-24. Confusion Matrix for Condition: S/N = -4 dB, Filtered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	39	17	7	
Tone 2	9	24	23	7
Tone 3	7	22	28	6
Tone 4	3	5	10	45

Subject 05:

Table D-25. Confusion Matrix for Condition: Quiet, Unfiltered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	63			
Tone 2		61	2	
Tone 3		1	62	
Tone 4			1	62

Table D-26. Confusion Matrix for Condition: Quiet, Filtered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	63			
Tone 2		60	3	
Tone 3		1	62	
Tone 4				63

Table D-27. Confusion Matrix for Condition: S/N = 0 dB, Unfiltered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	63			
Tone 2	5	53	4	1
Tone 3	18	29	15	1
Tone 4				63

Table D-28. Confusion Matrix for Condition: S/N = 0 dB, Filtered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	59	2	2	
Tone 2	4	48	10	1
Tone 3	18	32	12	1
Tone 4		1	1	61

Table D-29. Confusion Matrix for Condition: S/N = -4 dB, Unfiltered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	29	15	12	7
Tone 2	24	17	18	4
Tone 3	19	27	11	6
Tone 4	3	9	11	40

Table D-30. Confusion Matrix for Condition: S/N = -4 dB, Filtered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	51	9	1	2
Tone 2	16	30	12	5
Tone 3	21	18	19	5
Tone 4	4	8	7	44

Subject 06:

Table D-31. Confusion Matrix for Condition: Quiet, Unfiltered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	63			
Tone 2	3	60		
Tone 3		2	61	
Tone 4				63

Table D-32. Confusion Matrix for Condition: Quiet, Filtered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	63			
Tone 2		63		
Tone 3		3	60	
Tone 4			1	62

Table D-33. Confusion Matrix for Condition: S/N = 0 dB, Unfiltered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	62		1	
Tone 2	3	37	22	1
Tone 3	5	19	39	
Tone 4	2		2	59

Table D-34. Confusion Matrix for Condition: S/N = 0 dB, Filtered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	62		1	
Tone 2	2	48	13	
Tone 3	5	33	24	1
Tone 4		1	1	61

Table D-35. Confusion Matrix for Condition: S/N = -4 dB, Unfiltered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	27	20	12	4
Tone 2	17	23	23	
Tone 3	14	28	18	3
Tone 4	11	9	8	35

Table D-36. Confusion Matrix for Condition: S/N = -4 dB, Filtered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	45	14	4	
Tone 2	11	30	22	
Tone 3	16	33	14	
Tone 4	9	11	6	37

Subject 07:

Table D-37. Confusion Matrix for Condition: Quiet, Unfiltered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	61	2		
Tone 2	4	57	1	1
Tone 3			62	1
Tone 4				63

Table D-38. Confusion Matrix for Condition: Quiet, Filtered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	62	1		
Tone 2		62		1
Tone 3			63	
Tone 4		2		61

Table D-39. Confusion Matrix for Condition: S/N = 0 dB, Unfiltered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	61	1	1	
Tone 2	5	40	13	5
Tone 3	11	16	27	9
Tone 4				63

Table D-40. Confusion Matrix for Condition: S/N = 0 dB, Filtered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	53	5	5	
Tone 2	13	29	13	8
Tone 3	7	24	19	13
Tone 4	3	1	3	56

Table D-41. Confusion Matrix for Condition: S/N = -4 dB, Unfiltered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	37	10	12	4
Tone 2	17	13	15	18
Tone 3	10	15	17	21
Tone 4	7	12	7	37

Table D-42. Confusion Matrix for Condition: S/N = -4 dB, Filtered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	35	7	13	8
Tone 2	12	22	9	20
Tone 3	18	18	15	12
Tone 4	9	6	10	38

Subject 08:

Table D-43. Confusion Matrix for Condition: Quiet, Unfiltered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	63			
Tone 2		63		
Tone 3			63	
Tone 4				63

Table D-44. Confusion Matrix for Condition: Quiet, Filtered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	63			
Tone 2	1	61		1
Tone 3			63	
Tone 4				63

Table D-45. Confusion Matrix for Condition: S/N = 0 dB, Unfiltered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	61	2		
Tone 2	3	43	13	4
Tone 3	5	20	34	4
Tone 4				63

Table D-46. Confusion Matrix for Condition: S/N = 0 dB, Filtered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	55	5	3	
Tone 2	6	42	13	2
Tone 3	9	27	22	5
Tone 4	2	6	10	45

Table D-47. Confusion Matrix for Condition: S/N = -4 dB, Unfiltered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	19	12	26	6
Tone 2	3	21	32	7
Tone 3	3	21	31	8
Tone 4	3	16	16	28

Table D-48. Confusion Matrix for Condition: S/N = -4 dB, Filtered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	33	11	15	4
Tone 2	14	24	20	5
Tone 3	11	24	21	7
Tone 4	5	12	10	36

Subject 09:

Table D-49. Confusion Matrix for Condition: Quiet, Unfiltered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	62			1
Tone 2		62	1	
Tone 3			63	
Tone 4			1	62

Table D-50. Confusion Matrix for Condition: Quiet, Filtered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	63			
Tone 2		63		
Tone 3			63	
Tone 4		1		62

Table D-51. Confusion Matrix for Condition: S/N = 0 dB, Unfiltered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	63			
Tone 2		44	18	1
Tone 3	2	14	44	3
Tone 4				63

Table D-52. Confusion Matrix for Condition: S/N = 0 dB, Filtered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	58	2	2	1
Tone 2	2	47	13	1
Tone 3	1	15	40	7
Tone 4			1	62

Table D-53. Confusion Matrix for Condition: S/N = -4 dB, Unfiltered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	60		3	
Tone 2	5	37	15	6
Tone 3	10	9	36	8
Tone 4	1	1		61

Table D-54. Confusion Matrix for Condition: S/N = -4 dB, Filtered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	47	5	7	4
Tone 2	8	29	22	4
Tone 3	10	14	28	11
Tone 4	3	5	8	47

Subject 10:

Table D-55. Confusion Matrix for Condition: Quiet, Unfiltered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	63			
Tone 2		63		
Tone 3		1	62	
Tone 4				63

Table D-56. Confusion Matrix for Condition: Quiet, Filtered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	63			
Tone 2		63		
Tone 3			63	
Tone 4				63

Table D-57. Confusion Matrix for Condition: S/N = 0 dB, Unfiltered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	59	1	1	2
Tone 2	4	30	26	3
Tone 3	6	27	28	2
Tone 4	3	1	1	58

Table D-58. Confusion Matrix for Condition: S/N = 0 dB, Filtered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	60	1	2	
Tone 2	3	35	20	5
Tone 3	8	29	25	1
Tone 4				63

Table D-59. Confusion Matrix for Condition: S/N = -4 dB, Unfiltered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	39	11	6	7
Tone 2	12	21	18	12
Tone 3	11	27	10	15
Tone 4	11	8	5	39

Table D-60. Confusion Matrix for Condition: S/N = -4 dB, Filtered

	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	46	10	4	3
Tone 2	9	21	25	8
Tone 3	9	25	20	9
Tone 4	6	8	7	42

APPENDIX E
Real vs. Nonsense Stimuli

Table E-1. Word vs. Nonword Stimuli (The Chinese-English Dictionary, 1979)

	Tone 1	Tone 2	Tone 3	Tone 4
ba	word	word	word	word
ca	word	nonword	nonword	nonword
cha	word	word	word	word
da	word	word	word	word
fa	word	word	word	word
ga	nonword	word	nonword	nonword
ha	word	nonword	nonword	nonword
jia	word	word	word	word
ka	word	nonword	word	nonword
la	word	word	nonword	word
ma	word	word	word	word
na	nonword	word	word	word
pa	word	word	nonword	word
qia	word	nonword	word	word
ra	nonword	nonword	nonword	nonword
sa	word	nonword	word	word
sha	word	nonword	word	word
ta	word	nonword	word	word
xia	word	word	nonword	word
za	word	word	word	nonword
zha	word	word	word	word