To the Graduate Council:

I am submitting herewith a dissertation written by Denise Brochetti entitled "Acoustical Characteristics of Mastication Sounds: Application of Speech Analysis Techniques." I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Food Technology and Science.

Marjorie P. Penfield, Major Professor

We have read this dissertation
and recommend its acceptance:

Accepted for the Council:

Vice Provost
and Dean of The Graduate School

ACOUSTICAL CHARACTERISTICS OF MASTICATION SOUNDS: APPLICATION OF SPEECH ANALYSIS TECHNIQUES

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Degree

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Denise Brochetti

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DEDICATION

This dissertation is dedicated to William Charles Brochetti and Florence Marie Spak Brochetti, parents of the author.

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ABSTRACT

Food scientists have used acoustical methods to study characteristics of mastication sounds in relation to food texture. However, a model for analysis of the sounds has not been identified, and reliability of the methods has not been reported. Therefore, speech analysis techniques were applied to mastication sounds, and variation in measures of the sounds was examined. To meet these objectives, two experiments were conducted.

In the first experiment, a digital sound spectrograph generated waveforms and wideband spectrograms of sounds by 3 adult subjects (1 male, 2 females) for initial chews of food samples differing in hardness and fracturability. Acoustical characteristics were described and compared. For all sounds, formants appeared in the spectrograms, and energy occurred across a 0 to 8000-Hz range of frequencies. Bursts characterized waveforms for peanut, almond, raw carrot, ginger snap, and hard candy. Duration and amplitude of the sounds varied with the subjects.

In the second experiment, the spectrograph was used to measure the duration, amplitude, and formants of sounds for the initial 2 chews of cylindrical food samples (raw carrot, teething toast) differing in diameter (1.27, 1.90, 2.54 cm). Six adult subjects (3 males, 3 females) having normal occlusions and temporomandibular joints chewed the samples between the molar teeth and with the mouth open. Ten repetitions per subject were examined for each food sample. Analysis of estimates of variation indicated an inconsistent intrasubject variation in the acoustical measures. Food type and sample diameter also affected the estimates, indicating the variable nature of mastication. Generally, intrasubject variation was greater than intersubject variation. Analysis of ranks of the data indicated that the effect of sample diameter on the acoustical measures was inconsistent and depended on the subject and type of food.

If inferences are to be made concerning food texture from acoustical measures of mastication sounds, intrasubject variability must be stabilized. Research should be directed toward examining experimental techniques and designs to stabilize the variability. Possibilities include identifying factors that may covary with acoustical measures, developing procedures for screening and selecting subjects, establishing procedures for chewing food samples, and defining dimensions for food samples.

TABLE OF CONTENTS

CHAPTER		PAGE
I.	INTRODUCTION	1
II.	REVIEW OF LITERATURE	4
	1. Evaluation of Food Texture	4
	Texture Profile Method	4
	Mastication Sounds	6
	2. Perception of Food Sounds	7
	Crushing Sounds	7
	Mastication Sounds	8
	3. Acoustical Characteristics of Food Sounds	15
	Crushing Sounds	15
	Mastication Sounds	17
	4. Characteristics of Speech Sounds	21
	Speech Production	22
	Vowels and Consonants	24
	Acoustical Methods	26
	5. Mastication in Relation to Food Texture	30
	Masticatory Act	30
	Food Texture	31
III.	SOUND SPECTROGRAPHY AS A METHOD OF EVALUATING MASTICATION SOUNDS: A PRELIMINARY INVESTIGATION	34
	1. Introduction	34
	2. Methods and Materials	35
	Subjects	35
	Food Samples	35
	Recording	35
	Acoustical Analysis	37
	3. Results and Discussion	39
	Duration of Mastication Sounds	39
	Amplitude of Mastication Sounds	56
	Distribution of Acoustic Energy	58
	Formants of Mastication Sounds.	59
	4. Conclusions	61
IV.	VARIATION IN ACOUSTICAL MEASURES OF MASTICATION SOUNDS	65
	1. Introduction	65
	2. Materials and Methods	69
	Food Samples	69
	Subjects	71
	Mastication Sounds	77
	Acoustical Analyses	78

CHAPTER PAGE

Speech Sounds 85
Statistical Analyses 90
3. Results and Discussion 90
Characteristics of Food Samples 90
Characteristics of Subjects 94
Acoustical Characteristics of Mastication Sounds 108
Intrasubject Variability in Acoustical Measures of Mastication Sounds 120
Intersubject Variability in Acoustical Measures of Mastication Sounds 131
Effects of Diameter of Food Samples and Type of Food on Acoustical Measures of Mastication Sounds 140
4. Conclusions 173

LIST OF REFERENCES 178

APPENDIXES 185

A. CALCULATIONS FOR MEASURES OF COMPRESSION RATES AND DECIBELS 186

B. ANALYSIS OF VARIANCE TABLES 188

C. INTERACTION MEANS TABLES 206

VITA 222

LIST OF TABLES

TABLE — PAGE

II.1 – Studies of the perception of mastication sounds 9

III.1 – Type, brand, and size of food samples 36

IV.1 – Mean chew counts, chewing rates, and compression rates for the 10 volunteers 75

IV.2 – Average coefficients of variation for acoustical measures of mastication sounds 86

IV.3 – Means ± standard deviations of moisture content of the food samples (n=3 measurements). . . 91

IV.4 – Means ± standard deviations for distance to peak force (n=20 repetitions) 94

IV.5 – Means ± standard deviations for durations of vowels produced by the subjects (n=3 repetitions) 100

IV.6 – Means ± standard deviations for fundamental frequencies of vowels produced by the subjects (n=3 repetitions) 101

IV.7 – Fundamental frequencies (F_0) and formant frequencies (F) for the vowels ɑ, i, and u 102

IV.8 – Means ± standard deviations for frequencies of the first 3 formants of vowels produced by the subjects (n=3 repetitions) 104

IV.9 – Means ± standard deviations for amplitudes of the first 3 formants of vowels produced by the subjects (n=3 repetitions) 106

IV.10 – Means ± standard deviations of oral-cavity volume of the subjects (n=8 repetitions) 108

IV.11 – Significant sources of variation in estimates of variation for amplitude display parameters for sounds of the initial 2 chews of food samples 123

IV.12 – Significant sources of variation in estimates of variation for duration parameters of sounds for the initial 2 chews of food samples 124

TABLE PAGE

IV.13 – Significant sources of variation in estimates of variation for formant (F1-F5) frequencies of sounds for the 2 initial chews of food samples 125

IV.14 – Significant sources of variation in estimates of variation for formant (F1-F5) amplitudes of sounds for the 2 initial chews of food samples 126

IV.15 – Significant sources of variation in estimates of variation for oscilloscopic parameters of sounds for the 2 initial chews of food samples 127

IV.16 – Maximum-likelihood estimates of variance components for amplitude display parameters of sounds for the initial 2 chews of the food samples 132

IV.17 – Maximum-likelihood estimates of variance components for formant amplitudes (F1-F5) of sounds for the initial 2 chews of the food samples 133

IV.18 – Maximum-likelihood estimates of variance components for formant frequencies (F1-F5) of sounds for the initial 2 chews of the food samples 135

IV.19 – Maximum-likelihood estimates of variance components for duration parameters of sounds for the initial 2 chews of the food samples 137

IV.20 – Maximum-likelihood estimates of variance components for oscilloscopic parameters of sounds for the initial 2 chews of the food samples 138

B.1 – Mean squares (ms) and F values for Instron parameters of the food samples 189

B.2 – Mean squares (ms) and F values for oral-cavity volume of the subjects 189

B.3 – Mean squares (ms) and probabilities (p) for F-values for variances of amplitude display parameters for sounds of the initial 2 chews of food samples 190

TABLE PAGE

B.4 – Mean squares (ms) and probabilities (p) for F-values variances of duration parameters for sounds of the initial 2 chews of food samples . . . 191

B.5 – Mean squares (ms) and probabilities (p) for F-values for variances of formant frequencies (F1-F5) of sounds for the initial 2 chews of food samples 192

B.6 – Mean squares (ms) and probabilities (p) for F-values for variances of formant amplitudes (F1-F5) of sounds for the initial 2 chews of food samples 193

B.7 – Mean squares (ms) and probabilities (p) for F-values for variances of oscilloscopic parameters for sounds of the initial 2 chews of food samples 194

B.8 – Mean squares (ms) and probabilities (p) for F-values for ranks of variances for amplitude display parameters for sounds of the initial 2 chews of food samples 195

B.9 – Mean squares (ms) and probabilities (p) for F-values for ranks of variances for duration parameters for sounds of the initial 2 chews of food samples 196

B.10 – Mean squares (ms) and probabilities (p) for F-values for ranks of variances for formant (F1-F5) frequencies of sounds for the initial 2 chews of food samples 197

B.11 – Mean squares (ms) and probabilities (p) for F-values for ranks of variances for formant (F1-F5) amplitudes of sounds for the initial 2 chews of food samples 198

B.12 – Mean squares (ms) and probabilities (p) for F-values for ranks of variances for oscilloscopic parameters for sounds of the initial 2 chews of food samples 199

B.13 – Mean squares (ms) and F values for ranks of amplitude display parameters for sounds of the initial 2 chews of food samples 200

TABLE PAGE

B.14 – Mean squares (ms) and F values for ranks of frequency and amplitude of formants 1-5 for sounds of the initial 2 chews of food samples. . . . 201

B.15 – Mean squares (ms) and F values for ranks of duration parameters for sounds of the initial 2 chews of food samples 204

B.16 – Mean squares (ms) and F values for ranks of oscilloscopic parameters for sounds of the initial 2 chews of food samples 205

C.1 – Food type x sample diameter interaction means ± standard deviations for Instron parameters for food samples (n=20 repetitions) 207

C.2 – Subject x sample diameter interaction means ± standard deviations for amplitude display parameters for sounds of the first chew of food samples (n=10 repetitions) 208

C.3 – Subject x sample diameter interaction means ± standard deviations for amplitude (dB) of formants 2, 4, and 5 for sounds of the second chew of food samples (n=10 repetitions) . . . 209

C.4 – Subject x food type interaction means ± standard deviations for amplitude (dB) of formant 4 for sounds of the first chew of food samples (n=10 repetitions) 210

C.5 – Subject x food type interaction means ± standard deviations for amplitude (dB) of formants 4 and 5 for sounds of the second chew of food samples (n=10 repetitions) 210

C.6 – Subject x food type interaction means ± standard deviations for amplitude display parameters for sounds of the first chew of food samples (n=10 repetitions) 211

C.7 – Subject x sample diameter x food type interaction means ± standard deviations for amplitude display parameters for sounds of the initial 2 chews of food samples (n=10 repetitions) 212

TABLE PAGE

C.8 – Subject x sample diameter x food type interaction means ± standard deviations for frequency and amplitude of formants 1-5 for sounds of the initial 2 chews of food samples (n=10 repetitions) 214

C.9 – Subject x sample diameter x food type interaction means ± standard deviations for durations (msec) of sounds for the initial 2 chews of food samples (n=10 repetitions) 219

C.10 – Subject x sample diameter x food type interaction means ± standard deviations for oscilloscopic parameters for sounds of the initial 2 chews of food samples (n=10 repetitions) 220

LIST OF FIGURES

FIGURE PAGE

II.1 – Continuous spectrum (top) and waveform (bottom) for the vowel /i/ produced by an adult female . . . 16

II.2 – Narrowband spectrogram (top) and wideband spectrogram (bottom) for the vowel /i/ produced by an adult female 29

III.1 – Waveform (top) and wideband spectrogram (bottom) of the sounds for the initial 5 chews of a graham cracker by subject 1 (adult male) . . . 40

III.2 – Waveform (top) and wideband spectrogram (bottom) of the sounds for the initial 5 chews of melba toast by subject 1 (adult male) 41

III.3 – Waveform (top) and wideband spectrogram (bottom) of the sounds for the initial 3 chews of a ginger snap by subject 1 (adult male) 42

III.4 – Waveform (top) and wideband spectrogram (bottom) of the sounds for the initial 5 chews of a peanut by subject 1 (adult male) 43

III.5 – Waveform (top) and wideband spectrogram (bottom) of the sounds for the initial 4 chews of an almond by subject 1 (adult male) 44

III.6 – Waveform (top) and wideband spectrogram (bottom) of the sounds for the initial 4 chews of a carrot by subject 1 (adult male) 45

III.7 – Waveform (top) and wideband spectrogram (bottom) of the sounds for the initial 3 chews of hard candy by subject 1 (adult male) 46

III.8 – Waveform (top) and wideband spectrogram (bottom) of the sounds for the initial 5 chews of celery by subject 1 (adult male) 47

III.9 – Waveform (top) and wideband spectrogram (bottom) of the sounds for the initial 5 chews of malted milk ball by subject 1 (adult male) 48

III.10 – Waveform (top) and wideband spectrogram (bottom) of the sounds for the initial 4 chews of a corn snack by subject 1 (adult male) 49

FIGURE PAGE

III.11 – Waveform (top) and wideband spectrogram (bottom) of the sounds for the initial 5 chews of melba toast by subject 2 (adult female) 50

III.12 – Waveform (top) and wideband spectrogram (bottom) of the sounds for the initial 3 chews of a ginger snap by subject 2 (adult female) 51

III.13 – Waveform (top) and wideband spectrogram (bottom) of the sounds for the initial 4 chews of celery by subject 2 (adult female) 52

III.14 – Waveform (top) and wideband spectrogram (bottom) of the sounds for the initial 8 chews of melba toast by subject 3 (adult female) 53

III.15 – Waveform (top) and wideband spectrogram (bottom) of the sounds for the initial 8 chews of a ginger snap by subject 3 (adult female) 54

III.16 – Waveform (top) and wideband spectrogram (bottom) of the sounds for the initial 7 chews of a corn snack by subject 3 (adult female) 55

IV.1 – Generalized force-distance curves from an Instron Universal Testing Machine for "one-bite" compressions of carrot and Zwieback Teething Toast samples: D=distance (cm), F=fracturability (Kg), H=hardness (Kg), and P=peak force (Kg) 72

IV.2 – Block diagram of system for recording mastication sounds: MIC=microphone, PRE=preamplifier, PS=power supply, ATT=attenuator, and TR=tape recorder 79

IV.3 – Waveform (upper plot) and amplitude envelope (lower plot) of an amplitude display for the sound of the initial chew by subject 2 (adult female) for a raw carrot sample, 2.54 cm in diameter 83

IV.4 – Instron values for hardness (A), fracturability (B), and peak force (C) of raw carrot and teething toast samples as a function of sample diameter (n=20 repetitions) 93

FIGURE PAGE

IV.5 – Narrowband spectrogram (top) and corresponding wideband spectrogram (bottom) for the vowel /i/ produced by subject 2 (adult female) 96

IV.6 – Narrowband spectrogram (top) and corresponding wideband spectrogram (bottom) for the vowel /ɑ/ produced by subject 2 (adult female) 97

IV.7 – Narrowband spectrogram (top) and corresponding wideband spectrogram (bottom) for the vowel /u/ produced by subject 2 (adult female) 98

IV.8 – Average power spectra for the vowels /i/ (right); /ɑ/ (center); and /u/ (left) 99

IV.9 – Amplitude display (top) and wideband spectrogram (bottom) for the sounds of the initial 3 chews by subject 2 (adult female) for a raw carrot sample, 1.27 cm in diameter 109

IV.10 – Amplitude display (top) and wideband spectrogram (bottom) for the sounds of the initial 3 chews by subject 2 (adult female) for a raw carrot sample, 1.90 cm in diameter 110

IV.11 – Amplitude display (top) and wideband spectrogram (bottom) for the sounds of the initial 3 chews by subject 2 (adult female) for a raw carrot sample, 2.54 cm in diameter 111

IV.12 – Amplitude display (top) and wideband spectrogram (bottom) for the sounds of the initial 4 chews by subject 2 (adult female) for a teething toast sample, 1.27 cm in diameter . . . 112

IV.13 – Amplitude display (top) and wideband spectrogram (bottom) for the sounds of the initial 3 chews by subject 2 (adult female) for a raw carrot sample, 1.90 cm in diameter 113

IV.14 – Amplitude display (top) and wideband spectrogram (bottom) for the sounds of the initial 3 chews by subject 2 (adult female) for a raw carrot sample, 2.54 cm in diameter 114

FIGURE PAGE

IV.15 – Average power spectra for the sounds of the first chew by subject 2 (adult female) for raw carrot samples of the following diameters: 1.27 cm (right); 1.90 cm (center); and 2.54 cm (left) 116

IV.16 – Average power spectra for the sounds of the second chew by subject 2 (adult female) for raw carrot samples of the following diameters: 1.27 cm (right); 1.90 cm (center); and 2.54 cm (left) 117

IV.17 – Average power spectra for the sounds of the first chew by subject 2 (adult female) for teething toast samples of the following diameters: 1.27 cm (right); 1.90 cm (center); and 2.54 cm (left) 118

IV.18 – Average power spectra for the sounds of the second chew by subject 2 (adult female) for teething toast samples of the following diameters: 1.27 cm (right); 1.90 cm (center); and 2.54 cm (left) 119

IV.19 – Peak amplitude of sounds for the first chew as a function of subject (S1-S6) x sample diameter irrespective of food type (n=20 repetitions) 143

IV.20 – Variance of peak amplitude of sounds for the first chew as a function of subject (S1-S6) x sample diameter irrespective of food type (n=20 repetitions) 144

IV.21 – Average amplitude of sounds for the first chew as a function of subject (S1-S6) x sample diameter irrespective of food type (n=20 repetitions) 145

IV.22 – Variance of average amplitude of sounds for the first chew as a function of subject (S1-S6) x sample diameter irrespective of food type (n=20 repetitions) 146

IV.23 – Duration of sounds for the first chew as a function of subject (S1-S6) x sample diameter irrespective of food type (n=20 repetitions) . . . 147

FIGURE PAGE

IV.24 – Variance of duration of sounds for the first chew as a function of subject (S1-S6) x sample diameter irrespective of food type (n=20 repetitions) 148

IV.25 – Peak amplitude (A) and average amplitude (B) of sounds for the first chew as a function of food x subject (S1-S6) irrespective of sample diameter (n=30 repetitions) 149

IV.26 – Variance of peak amplitude (A) and average amplitude (B) of sounds for the first chew as a function of food x subject (S1-S6) irrespective of sample (n=30 repetitions) 150

IV.27 – Peak amplitude of sounds for the second chew as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions) 151

IV.28 – Variance of the peak amplitude of sounds for the second chew as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions) 152

IV.29 – Average amplitude of sounds for the second chew as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions) 153

IV.30 – Variance of the average amplitude of sounds for the second chew as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions) 154

IV.31 – Duration of sounds for the second chew as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions) 155

IV.32 – Variance of the duration of sounds for the second chew as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions) 156

IV.33 – Amplitude of the first formant of sounds for the first and second chews as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions) 158

FIGURE PAGE

IV.34 – Variance of the amplitude of the first formant of sounds for the first and second chews as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions) 159

IV.35 – Amplitude of the third formant of sounds for the first and second chews as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions) 160

IV.36 – Variance of the amplitude of the third formant of sounds for the first and second chews as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions) 161

IV.37 – Amplitude of the second formant of sounds for the first chew as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions) 162

IV.38 – Variance of the amplitude of the second formant of sounds for the first chew as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions) 163

IV.39 – Amplitude of the second formant of sounds for the second chew as a function of subject (S1-S6) x sample diameter irrespective of food type (n=20 repetitions) 164

IV.40 – Variance of the amplitude of the second formant of sounds for the second chew as a function of subject (S1-S6) x sample diameter irrespective of food type (n=20 repetitions) 165

IV.41 – Frequency of the first formant of sounds for the first and second chews as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions) 167

IV.42 – Variance of the frequency of the first formant of sounds for the first and second chews as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions) 168

IV.43 – Frequency of the second formant of sounds for the first and second chews as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions). 169

FIGURE PAGE

IV.44 – Variance of the frequency of the second formant of sounds for the first and second chews as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions) 170

IV.45 – Frequency of the third formant of sounds for the first and second chews as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions) 171

IV.46 – Variance of the frequency of the third formant of sounds for the first and second chews as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions) 172

CHAPTER I

INTRODUCTION

For some time, food scientists have tried to examine the texture of food as it is masticated. Imitative texture-measuring instruments, such as the Bite Tenderometer and the strain-gauge Denture Tenderometer, have been fitted with dentures to simulate the action of the mouth during mastication (Proctor et al., 1955, 1956a,b; Volodkevich, 1938). Problems with these instruments included adhesion of food to the dentures and absence of the effects of saliva and tongue. Recently, electromyography, which senses electrical potentials of the masticatory muscles, has been used to study the forces needed to break down gels and gum-based confectionary products (Amemiya, 1990; Boyar and Kilcast, 1986a; Eves et al., 1990).

Several researchers have studied mastication sounds to obtain information concerning food texture. These researchers include B.K. Drake, Z.M. Vickers and colleagues, and W.E. Lee III and colleagues. Vickers and colleagues investigated the perception of mastication sounds in relation to the crispness, crunchiness, and crackliness of foods (Christensen and Vickers, 1981; Edmister and Vickers, 1985; Vickers, 1981, 1984a,b, 1985, 1987; Vickers and Christensen, 1980). Lee et al. (1988, 1990) studied the intensity and spectrum of mastication sounds for consecutive chews of potato chips and tortilla chips in relation to the crispness of these foods. Drake focused on the acoustical characteristics of mastication sounds. The researcher examined the amplitudes, spectra, and frequency-amplitude-time characteristics of mastication sounds for various foods (Drake, 1963, 1965a,b, 1971). Studies published by these researchers are discussed in Chapter II.

Bourne (1985) reported that acoustical methods are indirect tests of food texture. Accordingly, information on the acoustical characteristics of mastication sounds is essential for developing acoustical methods for evaluating food texture. This was the

emphasis of this study. Additionally, speech served as a model for the study because of similarities between mastication sounds and speech sounds. Mastication sounds are produced within the oral cavity which is part of the vocal tract used for production of speech sounds. Consequently, speech sounds were analyzed in the study, and speech analysis techniques were applied to mastication sounds.

The primary objective of the study was to obtain information concerning the acoustical characteristics of mastication sounds. To meet this objective, 2 experiments were conducted.

In the first experiment (Chapter III), sound spectrography, a speech analysis technique, was applied to mastication sounds of food samples differing in textural properties. Three subjects produced the sounds which were evaluated. The following were the objectives of the experiment:

1. To use a digital sound spectrograph to generate waveforms and wideband spectrograms of mastication sounds for the initial chews of the food samples;
2. To describe acoustical characteristics of the mastication sounds from the waveforms and wideband spectrograms;
3. To compare acoustical characteristics of the mastication sounds for the food samples; and
4. To compare acoustical characteristics of the mastication sounds by the subjects.

In the second experiment (Chapter IV), acoustical measures of mastication sounds were studied for cylindrical food samples differing in diameter and textural properties. Acoustical measures studied were selected based on the results of the first experiment. Six subjects produced the sounds which were analyzed. The following were the objectives of the experiment:

1. To examine intrasubject variability in acoustical measures of mastication sounds for the initial 2 chews of the food samples;
2. To examine intersubject variability in acoustical measures of mastication sounds for the initial 2 chews of the food samples;

3. To examine the effect of sample diameter and food type on acoustical measures of mastication sounds for the initial 2 chews of the food samples; and
4. To evaluate relationships of acoustical measures of the mastication sounds to instrumental measures of hardness and fracturability for the food samples.

CHAPTER II

REVIEW OF LITERATURE

Because of the interdisciplinary nature of this study, literature from several scientific disciplines is included in this review. The first three sections pertain to food texture and its relationship to food crushing and mastication sounds. The fourth section pertains to speech sounds and the acoustical characteristics and analyses of these sounds. Finally, mastication in relation to food texture is discussed in the fifth section.

1. EVALUATION OF FOOD TEXTURE

Texture is a food attribute which is important to consumers. Researchers have found that consumers are aware of the texture of foods and understand the meaning of texture words (Szczesniak and Kleyn, 1963; Szczesniak, 1971; Szczesniak and Kahn, 1971; Szczesniak and Skinner, 1973). Bourne (1978) stated, "texture, appearance, and flavor are the three major components of food acceptability. . . . " Because texture is an important food attribute, reliable methods are needed to study the texture of food.

Texture Profile Method

The General Foods Texture Profile Method is the primary method for evaluating the texture of food. This method is based on Szczesniak's (1963) three main classes of textural characteristics including the mechanical, geometrical, and "other" characteristics. Mechanical characteristics, which relate to the reaction of food to stress, include primary parameters (hardness, cohesiveness, adhesiveness, viscosity, and elasticity) and secondary parameters (brittleness, chewiness, and gumminess). Whereas the geometrical characteristics refer to the size, shape, and arrangement of particles within a food, "other" characteristics refer to the fat and

moisture contents of a food (Szczesniak, 1963; Szczesniak and Kleyn, 1963).

Sensory and instrumental tests were developed for the Texture Profile Method. For sensory evaluation, standard rating scales were developed for the mechanical parameters (Brandt et al., 1963; Szczesniak et al., 1963; Szczesniak, 1975). Reference standards, which were foods having particular mechanical parameters as their primary characteristics, were selected to represent points on these scales. Sensory evaluation procedures were divided into the first-bite, masticatory, and residual phases to assess all of the characteristics present in a test food, the degree that each is present, and the order in which they appear (Brandt et al., 1963).

For instrumental testing, the General Foods Texturometer (GFT) was developed to evaluate the mechanical parameters of "bite-size" samples of foods (Friedman et al., 1963; Szczesniak et al., 1963; Szczesniak and Einstein, 1974; Szczesniak, 1975). The GFT was designed to simulate the action of the human jaw during mastication. Therefore, it compresses samples at non-uniform rates to produce force-time curves from which the mechanical parameters of texture are evaluated.

Since the development of the Texture Profile Method, researchers have modified the method to improve its accuracy and reliability. Two of the mechanical parameters were renamed to better reflect their corresponding sensory properties. Fracturability replaced the term brittleness, and springiness replaced the term elasticity (Szczesniak, 1975). Bourne et al. (1966) and Bourne (1968, 1978) adapted the Instron Universal Testing Machine to the analysis of food texture. Whereas the GFT applies a non-uniform compression to a test sample, the Instron applies a uniform compression producing force-time or force-distance curves. From these curves, values for force, work, distance, and slope are obtained and used to calculate the mechanical parameters. Recently, Muñoz (1986) modified the sensory evaluation procedures of the Texture Profile Method. Definitions were expanded for the mechanical and geometrical

characteristics, and new reference standards were selected for the rating scales.

Despite modifications, researchers recognize the limitations of the Texture Profile Method. Szczesniak (1977) stated, "There is growing awareness that instrumental texture measurements should be performed under conditions simulating as closely as possible those occurring during sensory evaluation. . . ." Boyar and Kilcast (1986b) emphasized that texture is perceived during mastication in which there are ". . . continuous changes in the physical properties of food caused by comminution and dilution with saliva, in addition to temperature changes. . . ." Hutchings and Lillford (1988) proposed that for "A Thorough understanding of product texture . . . emphasis ought to be placed on the food material and its breakdown. . . ."

Mastication Sounds

Mastication sounds have been referred to in relation to food texture, indicating that these sounds are of interest to food scientists. Szczesniak (1963) stated,

> Sound effects, such as those occurring during eating of popcorn and celery, are related to the physical constitution of the food and should be regarded as part of the over-all textural effect.

Additionally, Szczesniak (1971) found that consumers are aware of sounds produced during mastication and handling of food. For word association tests in which consumers responded to each of 29 foods, sound-related words in decreasing frequency of occurrence were crunchy, noise, crackling, and sounds. Recently, Szczesniak (1988) asked 200 consumers to describe crispness and give three examples of crisp foods. The most frequent examples were lettuce, crackers, cold cereal, celery, and potato chips. Crunchy and crackly were the sound-related terms used most often to describe crispness. Therefore, Szczesniak defined a crisp food as ". . . one that is firm (stiff) and snaps easily (rather than bends) when deformed emitting a crunchy/crackly sound. . . . " Szczesniak

proposed that ". . . the 'snap' has a bearing on the short duration of the sound. . . ."

Jowitt (1974) stated that hearing is one of the senses used to perceive brittleness, crunchiness, crispness, grittiness, and glassiness. Additionally, Jowitt (1974) defined crisp in relation to fruits and vegetables as ". . . a tendency when subjected to an applied force to yield suddenly with a characteristic sound . . . ." Vickers and Bourne (1976) proposed a "psychoacoustical" theory for crispness. The researchers considered sound as the link between the physical and psychological realms.

2. PERCEPTION OF FOOD SOUNDS

Vickers and colleagues, in a series of studies, examined the perception of food crushing and mastication sounds in relation to food texture. A thorough review of these studies is included to provide information concerning methodologies and hypotheses.

Crushing Sounds

Vickers and Wasserman (1979) used nonmetric multidimensional scaling (MDS) to study the similarity of sounds produced when foods were manually crushed and to identify characteristics that distinguished the sounds. Eighteen different foods were crushed with rubber-coated pliers at uncontrolled rates of force application and deformation. A microphone was placed 3 cm from the foods while they were crushed, and recordings were made of the sounds. Recorded sounds then were delivered through earphones to 20 subjects who judged the similarity of all possible pairs of the sounds. Subjects also evaluated each of the sounds for 15 sensory characteristics. A dissimilarity matrix was computed for the judgments. Characteristics which occurred close together in the matrix were loud, crunchy, crackly, crisp, brittle, sharp, snap, and hard.

Vickers (1980) also examined the ability of subjects to identify foods based on their crushing sounds. The food samples and procedures were identical to those in the previous study. Thirty subjects were told how the sounds were produced and were given a list of the foods from which they selected and ranked the 4 foods most likely to have produced the sounds. Vickers found that some foods were more frequently identified than others based on their crushing sounds. However, the researcher was unable to explain the results based on familiarity with and class of the foods but suggested that differences in sound quality may be an explanation.

Mastication Sounds

Subsequent studies were conducted with mastication sounds. Listed in Table II.1 are the studies of the perception of mastication sounds. To simplify review of these studies, each has been numbered and the corresponding experimental techniques, psychoacoustical characteristics, textural characteristics, and references have been indicated. Throughout this section of the review, studies are referred to by the numbers.

The primary objective of these studies was to determine if crispness, crunchiness, and crackliness were auditory sensations. To meet this objective, a variety of experimental techniques were used. These techniques included the oral technique, auditory technique, auditory masking, and several mastication techniques (Table II.1). Because the techniques may have affected the results of the studies, each technique is discussed prior to review of the studies.

Experimental techniques

Both oral and auditory techniques were used to evaluate mastication sounds. For the oral technique, subjects masticated foods for evaluation. For the auditory technique, subjects listened to recordings of mastication sounds produced by the

Table II.1 – Studies of the perception of mastication sounds

Study number	Experimental technique	Characteristic		Reference
		Psychoacoustical	Textural	
1	Oral Mastication Masking	Loudness	Crispness	Christensen and Vickers, 1981
2	Oral Mastication	Loudness	Crispness Firmness	Vickers and Christensen, 1980
3	Oral Mastication	Loudness Pitch	Crispness Crunchiness	Vickers, 1984a
4	Auditory Mastication	Loudness Pitch	Crispness Crunchiness	Vickers, 1985
5	Oral Auditory	---	Crispness Crunchiness Hardness	Vickers, 1981
6	Oral Auditory	---	Crispness	Edmister and Vickers, 1985
7	Oral Auditory Masking	---	Crackliness	Vickers, 1984b

investigators for evaluation. For the recordings, the researchers stated that sounds were sensed by a microphone held against the outer ear, immediately above the opening of the ear canal of the investigators (Vickers, 1981). Either headphones or earphones were used to deliver sounds to the subjects. Whereas the oral technique was used primarily in studies 1-4, the auditory technique was used primarily in studies 5-7 to isolate oral-tactile information from auditory information.

Three different mastication techniques were used to study mastication sounds. These techniques were used by both the subjects and the investigators. The three techniques included the "bite-only", "chew-only", and the "bite + chew" techniques. For the "bite-only" technique, food samples were bitten only once with the incisors. For the "chew-only" technique, food samples were masticated with the molars. Samples were bitten once with the incisors then chewed at least twice with the molars for the "bite + chew" technique. At least 2 of the 3 techniques were used in studies 1-4, because the researchers hypothesized that mastication technique affected the loudness and pitch of mastication sounds. The "bite-only" technique was expected to produce lightly damped sounds with a greater amount of air-conducted sounds than the other two techniques. Therefore, sounds produced with this mastication technique were expected to be rated louder and higher in pitch than those produced by the other techniques (Christensen and Vickers, 1981; Vickers, 1984a).

Auditory masking was used in studies 1 and 7 to determine if auditory information was essential to the perception of crispness and crackliness of foods. In these studies, the oral technique was used, and subjects evaluated textural characteristics in the presence and absence of a masking noise. Headphones were used to deliver the noise to the subjects. The researchers reported that the noise was static between channels of an FM tuner, but they did not report whether the noise was delivered directly to the subjects or whether the noise was recorded then delivered to the subjects. The latter method could provide more control over the

quality of the masking noise than the former method. The researchers also reported that the noise had an intensity of 100 dB, a center frequency of 150 Hz, and a bandwidth of 90-230 Hz. Although the researchers referred to the masking noise as white noise (Christensen and Vickers, 1981; Vickers, 1984b), the acoustical characteristics indicate that it was a narrowband low-frequency masking noise.

Studies

The relationship of loudness to crispness and firmness was investigated in studies 1 and 2 (Christensen and Vickers, 1981; Vickers and Christensen, 1980). The oral technique was used, and the "bite-only" and "chew-only" mastication techniques were examined. Subjective estimates of loudness, crispness, and firmness were obtained. Twenty subjects and the same 16 food samples were used in both studies. In study 2, physical measures of firmness, stiffness, and peak force were correlated with the subjective estimates. A triple beam snap test cell attached to an Instron was used to obtain these measures.

In study 1 (Christensen and Vickers, 1981), the researchers found that the slopes of regression equations relating loudness to crispness for all food samples were approximately 1.00, indicating a strong relationship between these characteristics. Correlation coefficients for the mastication techniques were high for loudness ($r=0.95$) and for crispness ($r=0.97$). Therefore, the researchers concluded that mastication technique had little effect on judgments of crispness and loudness. Additionally, they concluded that subjects attended to information in the first bite, because this was the commonality for the mastication techniques. However, they were unable to attribute results to auditory information alone, because the oral technique was used for evaluation. Therefore, the effect of oral-tactile information on judgments could not be eliminated. Similar results were obtained in study 2 (Vickers and Christensen, 1980), but a stronger correlation was found between loudness and crispness ($r=0.97$) than between

firmness and crispness (r=0.83). Crispness also correlated with the physical measure of stiffness, and firmness correlated with peak force.

Based on the results of these studies, the researchers concluded that crispness had both oral-tactile and auditory components and proposed a "vibrotactile-acoustical" hypothesis for the sensation of crispness, although acoustical measures were not reported for the sounds. The researchers explained that repeated breaking and fracturing of foods during mastication produces vibrations that stimulate both oral-tactile and auditory systems (Vickers and Christensen, 1980).

Two experiments were conducted in study 3 (Vickers, 1984a) to examine the relationship of the pitch of mastication sounds to crispness and crunchiness. The objective of the first experiment was to determine if pitch distinguished these textural characteristics. First, 20 subjects rated the crispness and crunchiness of 23 food samples. Of these samples, 5 were rated more crisp than crunchy, and 7 were rated more crunchy than crisp. Subjects then compared the pitch of the sounds for all possible pairs of these 12 food samples. Whereas crisp foods were judged higher in pitch than the crunchy foods, crunchy foods never were judged higher in pitch than the crisp foods. Therefore, the researcher concluded that pitch distinguished crispness and crunchiness, and conducted a second experiment to examine the effect of mastication technique on pitch. However, the pitch of the mastication sounds was not directly evaluated in the second experiment. Subjects judged the crispness and crunchiness of their sounds for the 12 food samples. The "bite-only" and "chew-only" techniques were examined. Whereas crispness scores were significantly higher for the "bite-only" technique, no significant difference in crunchiness scores was found for the 2 techniques. Because crunchiness scores were unaffected, Vickers suggested that mastication technique affected characteristics other than pitch of the sounds. The researcher added that oral-tactile sensations and loudness may have differed for the 2

techniques, but loudness scores were not reported for the sounds to support this explanation.

In study 4 (Vickers, 1985), the effect of mastication technique on pitch was re-examined. Both pitch and loudness were evaluated for mastication sounds of 23 food samples. The auditory technique was used to eliminate the effect of oral-tactile information. The same mastication techniques as those in study 3 were examined. Subjects also rated the crispness and crunchiness of the foods. Results were similar to those of study 3. Sounds of crisper foods were rated louder and higher in pitch than those of crunchier foods; however, mastication technique had no effect on crispness and crunchiness scores.

The hypothesis that auditory information was essential to the perception of crispness, crunchiness, and hardness was examined in studies 5 and 6 (Vickers, 1981; Edmister and Vickers, 1985). Twenty subjects, 16 foods, and the "bite + chew" mastication technique were used. Also oral and auditory techniques were used to isolate oral-tactile information from auditory information.

In study 5 (Vickers, 1981), high positive correlations between oral and auditory techniques were found for crispness ($r=0.89$), crunchiness ($r=0.95$), and hardness ($r=0.89$) scores. Therefore, Vickers concluded that auditory information was essential to the perception of these characteristics but added that the results for hardness were unexpected, because hardness has been considered primarily an oral-tactile sensation. Although the researcher explained that subjects may have equated loudness with hardness, loudness scores were not reported to support this explanation. In contrast, results of study 6 indicated a weaker correlation ($r=0.68$) of oral and auditory techniques for crispness scores (Edmister and Vickers, 1985). The researchers suggested that auditory information alone was insufficient for judgments of crispness and indicated that factors such as size, shape, and identity of the foods may have affected the results.

Auditory masking was used in a second experiment of study 1 to examine the importance of auditory information to judgments of

crispness (Christensen and Vickers, 1981). The oral technique and the "bite + chew" mastication technique were used. Twenty subjects rated the crispness of 16 food samples. As a control, subjects rated the thickness of aqueous solutions containing different levels of sodium alginate, because thickness was considered primarily an oral-tactile sensation. A high positive correlation (r=0.99) was found between crispness scores for auditory masking and the oral technique. However, variability in scores was lower for masking than for the oral technique, and the magnitude of the scores was higher for masking than for the oral technique. Similar results were obtained for thickness, but the magnitude of these scores was lower for masking than for the oral technique. Differences in magnitude between the two techniques was attributed to shifts in the use of number scales, because subjects used magnitude estimation for judgments. However, the masking conditions also may have affected the results.

Based on the results of studies 1, 5, and 6, the researchers concluded that auditory information was not essential to the perception of crispness. Furthermore, they suggested that oral-tactile and auditory information are redundant for crispness. However, the researchers emphasized that this does not disprove the "vibrotactile-acoustical" hypothesis for crispness (Edmister and Vickers, 1985).

Finally, auditory masking was used in study 7 to determine if auditory information was essential to the perception of crackliness (Vickers, 1984b). Procedures were similar to those used in study 1, but the auditory technique (recorded sounds) also was used. A high positive correlation (r=0.96) was found in crackliness scores for the auditory masking and oral technique. Also, a high positive correlation (r=0.95) was found in crackliness scores for the auditory technique and the oral technique. Based on these results, Vickers concluded that auditory information was essential to the perception of crackliness. However, masking conditions may have influenced the results.

3. ACOUSTICAL CHARACTERISTICS OF FOOD SOUNDS

Food scientists have studied food crushing and mastication sounds to identify acoustical characteristics that distinguish food textures. For evaluation, oscilloscopic analysis and Fast Fourier Transform (FFT) have been used. In general, oscilloscopic analysis produces a waveform which is a plot of sound pressure variations over time (Denes and Pinson, 1963; Melnick, 1973). An example of a waveform for the vowel /i/ is shown in Figure II.1. FFT generates a sound spectrum which displays amplitude as a function of frequency at a given instant in time (Perkins and Kent, 1986; Cudahy, 1988). An example of a spectrum for the vowel /i/ is shown in Figure II.1.

Crushing Sounds

Mohamed et al. (1982) studied crushing sounds of friable foods. A constant loading rate texture technique was used to test foods in an anechoic chamber. Mechanical parameters of force and work were evaluated, and sounds were recorded during testing. A statistical distribution analyzer was used to determine equivalent continuous sound levels (L_{eq}) of the recorded sounds. An experienced sensory panel evaluated the hardness, rate of breakdown, sound intensity (loudness), and crispness of identical food samples while chewing the foods with their mouths open. Results of regression analysis indicated that sensory crispness correlated significantly with sensory sound intensity. Also, significant correlations were found among L_{eq} and mechanical parameters. Whereas mechanical parameters were the best predictors of sensory crispness, L_{eq} was the next best predictor.

Seymour and Hamann (1988) used a shear-compression cell to crush foods in an acoustically insulated chamber. Crushing sounds were recorded and analyzed. For frequencies of 500-3300 Hz, the following were measured: sound pressure (N/m^2), sound pressure level (dB), and sound intensity (W/m^2). The maximum force to

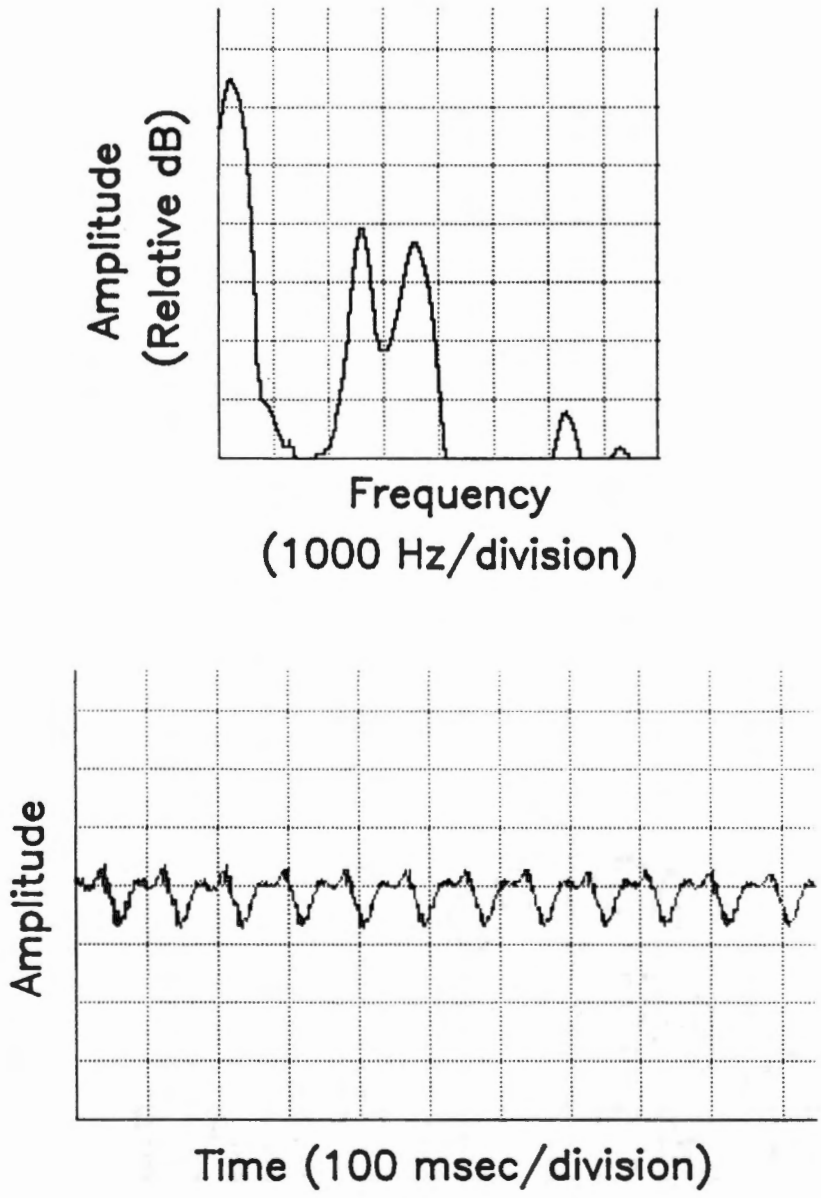


Figure II.1 – Continuous spectrum (top) and waveform (bottom) for the vowel /i/ produced by an adult female. Amplitude increases from bottom to top of the spectrum. Frequency and time increase from left to right.

fracture and work to fracture were measured from force-deformation curves for the foods. Additionally, a trained texture profile panel evaluated the crispness and crunchiness of the foods. For evaluation, the panel defined crispness as the "level of higher pitched noise on the first-bite with the molars" and crunchiness as the "degree of low pitched noise during mastication with the molars." Results indicated a strong positive correlation between crispness and crunchiness scores. The researchers also reported stronger correlations between mechanical measures and sensory scores than between acoustical measures and these scores. However, when acoustical measures were included in the regression equation relating mechanical measures to sensory scores the relationship was strengthened.

Mastication Sounds

Drake (1963) was the first to study the acoustical characteristics of mastication sounds. Sounds were recorded, beginning with either the second or third chew, 5 cm from the mouths of subjects who chewed food samples with their mouths open. Spectra were generated for the recorded sounds. Results indicated that spectra were similar for the sounds produced by 5 subjects who chewed crisp brown bread. Peaks occurred at frequencies of 1250, 5000, 8000, and 10000 Hz, indicating that acoustic energy was concentrated at these frequencies. For two subjects who chewed bread samples toasted to different degrees, similar spectra were obtained for samples toasted to the same degree. Peaks occurred at frequencies similar to those for crisp brown bread; however, amplitude increased as the degree of toasting of the bread increased. Spectra for mastication sounds also were compared with those for food crushing sounds. Crushing sounds were recorded 5 cm from a wooden block used to crush food samples against the surface of a table. Results indicated that acoustic energy was concentrated in different frequency regions for the two types of sounds.

Drake (1965a) also studied the relationship between the amplitude of sound waves produced during mastication and the loudness of these sounds. Sounds were recorded and analyzed for 6 subjects who chewed samples of carrots and Swedish biscuits (crackers). Sounds were recorded with a high impedance hearing-aid microphone which was connected to plastic tubing that was inserted into the ear canal of the subjects. Subjects also judged the loudness of their mastication sounds during recording. An oscilloscope was used to analyze sound amplitude, and the peak amplitudes of the first five chews were averaged. Results indicated that loudness scores increased as sound amplitude increased.

Drake (1965b, 1971) used a "visible speech" technique to examine the frequency-amplitude-time characteristics of mastication sounds produced by 6 subjects. Sounds for 4 types of vegetables and 5 types of breads were analyzed. The researcher reported that measures of these characteristics differed significantly among foods and among subjects; however, differences among foods were at least as large as those among subjects. However, Drake emphasized that sizes of the food samples differed and that this difference may have affected the results of the study. The researcher suggested that "visible speech" could be used to obtain information for mastication sounds and that it may be a means of selecting appropriate conditions for other types of analyses.

Based on the results of these studies, Drake suggested that acoustical analysis of mastication sounds may provide information concerning the texture of food. However, the researcher stressed that many foods, subjects, and acoustical characteristics must be examined. Despite these suggestions, there has been a limited number of studies concerning the acoustical characteristics of mastication sounds.

Vickers and Bourne (1976) used oscilloscopic analysis and FFT to examine sounds produced by a variety of crisp foods. The researchers produced the sounds by biting foods with the incisors

and by manually breaking the foods. Results indicated that crisp food sounds had broad-band spectra with acoustic energy occurring at frequencies up to 10000 Hz. However, no other spectral characteristics were reported, and no distinctions were made between sounds for foods that were bitten and manually broken. The researchers also reported that crisp food sounds had uneven or irregular waveforms; therefore, they concluded that an irregular series of loud noises characterized crispness. However, measures of sound amplitude and loudness were not reported. Based on the results, the researchers proposed a "psychoacoustical" theory for crispness and a "cellular" model describing how crisp foods produced sounds. The researchers explained that crushing causes the cell walls of crisp foods to rupture, thereby producing a series of loud noises.

Vickers (1984b, 1987) and Edmister and Vickers (1985) used oscilloscopic analysis to examine noise bursts of mastication sounds for crisp and crackly foods. Noise bursts, in general, are associated with impulses or "pop-like" sounds which have transient sound sources. Bursts have short durations and broad-band spectra in which acoustic energy is distributed over a broad bandwidth of frequencies (Denes and Pinson, 1963; Minifie, 1973; Shoup and Pfeifer, 1976).

In these studies of noise bursts, recorded sounds were analyzed. Recordings were made of sounds produced by one of the researchers biting foods with the incisors then chewing with the molars. From waveforms of the sounds, values were determined for the following acoustical characteristics for the "bite" and "first chew": duration, number of noise bursts, and mean amplitude of the bursts. Additionally, subjects judged either the crackliness or crispness of the recorded sounds. Sounds were delivered to subjects through either headphones or earphones.

Vickers (1984b) found a strong correlation (r=0.95) between crackliness scores for mastication sounds and the number of noise bursts for both the "bite" and the "first chew" plus the mean amplitude of the bursts. Strong correlations also were noted

between crackliness scores and the number of noise bursts on the "bite" (r=0.92) and on the "bite + first chew" (r=0.94). Therefore, Vickers concluded that noise bursts were indicators of crackliness.

Edmister and Vickers (1985) had subjects evaluate the crispness of recorded mastication sounds (auditory judgments) and the crispness of foods with the "bite + chew" mastication technique (oral judgments). The researchers found that correlations between measures of noise bursts and crispness scores were stronger for auditory judgments than for oral judgments. Additionally, the researchers reported that the best predictor of crispness was the logarithmic relationship between auditory judgments and the number of noise bursts times the mean amplitude of the bursts. However, acoustical analysis was limited to recordings of sounds produced by the researchers and only the "bite" portion of these sounds. In contrast, oral judgments were based on the mastication sounds produced by the subjects.

Vickers (1987) also examined noise bursts of mastication sounds for 5 brands of potato chips. Subjects evaluated crispness of the chips (oral judgments) and the crispness of recorded sounds of the chips (auditory judgments). Recordings were of sounds produced by 4 individuals biting and chewing the chips. Measures of noise bursts were obtained only for the "bite" portion of the recorded sounds. The following mechanical measures for the chips were obtained from force-deformation curves: force; slope of the curves; and area under the curves. Vickers found that all mechanical measures were inversely related to oral judgments and unrelated to auditory judgments of crispness. A strong correlation (r=0.99) was found for oral judgments and a combination of number of noise bursts, mean amplitude of the bursts, and either force or slope of the force-deformation curves. Therefore, Vickers concluded that a combination of mechanical and acoustical measures was a better predictor of potato chip crispness than either mechanical or acoustical measures alone.

Lee et al. (1990) studied the intensity of mastication sounds for fresh and stale potato chips and tortilla chips. The A-weighting scale of a sound level meter was used to measure the intensity of each of 15 consecutive chews. This scale was used because it has a frequency response designed to approximate the sensitivity of the human ear. Sounds were sensed by a microphone held 20 cm from the mouths of subjects who chewed chips with their mouths closed. Additionally, subjects evaluated the crispness for each chew of identical samples. The researchers found that for all samples sound intensity decreased with each successive chew; however, no significant differences in intensity were found between the fresh and stale chips. In contrast, crispness scores significantly differed for the fresh and stale chips.

Lee et al. (1988) compared spectra of mastication sounds for fresh and stale potato chips and tortilla chips. Spectra were analyzed for 7 of 10 consecutive chews by subjects who chewed the chips with their mouths closed. Spectra of each chew were averaged for the subjects. Results indicated that acoustic energy was present in the range of 0-12000 Hz for the potato chips and in the range of 0-9000 Hz for the tortilla chips. For the first chew of fresh potato chips, spectral peaks were noted within the regions of 3000-4000 Hz and at 6000 Hz. Similar but less pronounced spectral peaks were observed for the first chew of fresh tortilla chips. Results for the stale potato chips were similar to those for the stale tortilla chips. Spectral peaks noted for the first chew of the fresh chips were absent for the first chew of the stale chips. Also, the amplitudes of the peaks were lower for the stale chips than for the fresh chips. The researchers concluded that spectra of mastication sounds differed for fresh and stale chips.

4. CHARACTERISTICS OF SPEECH SOUNDS

In this section, the production and characteristics of speech sounds are discussed. These areas have been reviewed extensively

in the speech science literature. The following discussion is based on a limited number of reviews.

Speech Production

Denes and Pinson (1963) stated that speech sounds are complex signals which are produced within the vocal tract by movements of the vocal organs. A "source-filter" model is used to represent the production of speech sounds (Handel, 1989; Tosi, 1979). According to this model, the vocal tract acts as a sound source and as an acoustic filter.

Energy for speech is a stream of air from the lungs. Several sound sources or mechanisms set the air into vibration to make it audible. These mechanisms include vibrations of the vocal folds, constrictions within the vocal tract, and momentary obstructions of air flow with the tongue or lips (Denes and Pinson, 1963; Minifie, 1973).

Speech sounds produced with vibrations of the vocal folds are referred to as voiced speech sounds. Fundamental frequency (F_0) is the average rate of vocal fold vibration for production of voiced speech sounds (Denes and Pinson, 1963; Zemlin, 1988). Fundamental frequency varies with the speaker and is related to mass and length of the vocal folds. As the mass and length of the vocal folds increase, F_0 decreases indicating that the rate of vocal fold vibration decreases. Consequently, adult males on the average have lower F_0s than adult females (Denes and Pinson, 1963; Minifie, 1973; Peterson and Barney, 1952). Zemlin (1988) reported average F_0s of 130 Hz for adult males and 220 Hz for adult females.

For production of speech sounds, energy is transferred from the sound source to the vocal tract causing the tract to vibrate. Because the vocal tract is a tube closed at one end and opened at the other, it acts as an acoustic filter or resonator (Denes and Pinson, 1963; Perkins and Kent, 1986). Therefore, the vocal tract has a natural or resonant frequency of vibration. Specifically,

the vocal tract has a set of resonant frequencies because the cross-sectional area of the tract varies along its length. The vibrating tract then acts as an acoustic filter to modify speech sound waves produced by the sound sources. The tract amplifies frequency components of the complex speech waves that are either at or near its resonant frequencies (Denes and Pinson, 1963; Minifie, 1973; Small, 1973).

Resonances of the vocal tract are referred to as formants, and resonant frequencies are referred to as formant frequencies. Formant frequencies depend on the configuration of the vocal tract. Each configuration of the tract has a characteristic set of formant frequencies. Therefore, changing the configuration of the vocal tract changes its acoustical properties (Denes and Pinson, 1963; Perkins and Kent, 1986). Articulation is the process of changing the configuration of the vocal tract for production of the different speech sounds. Some of the articulatory movements which change the configuration and acoustical properties of the vocal tract include opening of the jaw, rounding or spreading of the lips, and position of the tongue. Consequently, the acoustical characteristics of speech sounds at the mouth opening depend on the source which produces the sound and the configuration of the vocal tract (Denes and Pinson, 1963; Minifie, 1973; Zemlin, 1988).

Distinctive features refer to the characteristics of speech sounds which relate to their production and perception (Tosi, 1979). In general, the duration of speech sounds ranges from 30-300 msec (Lehiste, 1970). Although the frequency components of speech sounds are within the 1 to 8000-Hz range, most information for recognition of speech sounds is within the 100 to 4000-Hz range (Minifie, 1973).

Speech scientists are aware of intraspeaker and interspeaker variability in speech sounds. Variability has been related to learned speaking differences, and anatomical, physiological, and psychological differences at the time of utterance (Denes and Pinson, 1963; Tosi, 1979).

Vowels and Consonants

In the English language, there are approximately 40-45 distinctively different speech sounds (Minifie, 1973). The 2 major categories of speech sounds are vowels and consonants.

Vowels

Vowels are continuent and voiced sounds. Related to the vowels are the diphthongs and semi-vowels. Whereas diphthongs, such as /ei/ as in "take", are composed of 2 vowels, semi-vowels, such as /w/, are produced with some degree of constriction within the vocal tract (Denes and Pinson, 1963; Minifie, 1973).

Distinctions among vowels are based on the position of the tongue. Tongue positions, including high, low, front, and back, are described by specifying the location of the main body of the tongue. Tongue positions for all vowels are described in reference to tongue positions for a set of standard reference sounds which are referred to as the cardinal vowels (Denes and Pinson, 1963; Handel, 1989; Zemlin, 1988). Denes and Pinson (1963) stated that cardinal vowels are sounds ". . . whose quality is defined independently of any language. . . ." Although Handel (1989) stressed that the cardinal vowel system represents auditory qualities, Denes and Pinson (1963) and Zemlin (1988) reported that X-ray studies indicate an agreement between vowel quality and tongue position. There are 8 cardinal vowels which represent the physiological limits of the tongue for production of all vowels. Three in particular represent the physiological extremes. These include /i/ as in "beet", /u/ as in "boot", and /ɑ/ as in "father". Whereas /i/ is produced with the tongue high and in the front of the oral cavity, /ɑ/ is produced with the tongue low and in the back of the oral cavity. For the production of /u/, the tongue is high and in the back of the oral cavity (Denes and Pinson, 1963; Zemlin, 1988).

Changes in the position of the tongue and lips are the articulatory movements used for production of the different vowel

sounds. Specifically, these movements change the configuration and acoustical properties of the vocal tract. Consequently, the resonances, or formants, of the vocal tract differ for different vowels. Each vowel has a characteristic set of formants. Although 4 or 5 formants are associated with any given vowel, the first 3 formants are important, perceptually, to the recognition of a vowel. Bandwidth (range of frequencies), center frequency, and amplitude are used to describe formants (Denes and Pinson, 1963; Perkins and Kent, 1986; Zemlin, 1988).

Zemlin (1988) reported that the length of the vocal tract affects formant frequencies. In particular, the frequencies of all formants decrease as the length of the tract increases. Zemlin (1988) also reported that the frequency of the first formant increases as the degree of jaw opening increases.

Peterson and Barney (1952) investigated the formant frequencies of 10 different vowels. For all vowels, frequencies of the first 3 formants were lower for vowels produced by adult males than for vowels produced by children and adult females. Differences were attributed to differences in the size of the vocal tract with adult males having larger vocal tracts than children and adult females.

Consonants

Consonants are described by voicing and place and manner of articulation. Whereas voiced consonants, such as /v/, are produced with vocal fold vibration, voiceless consonants, such as /f/, are produced without vibration of the vocal folds (Denes and Pinson, 1963).

Major classes of consonants by manner of articulation include fricatives, stops (plosives), affricatives, and nasals. Fricatives, such as /s/, are produced with constriction within the vocal tract. Stops, such as /t/, are produced by initially obstructing air flow causing a build up of air pressure. This is followed by release of the obstruction and drop in air pressure. Affricatives, such as /dʒ/ as in "Joe", are produced with

obstruction and constriction within the vocal tract. Finally, nasals, such as /m/, are produced by blocking air flow through the mouth and directing sound radiation through the nasal cavity (Denes and Pinson, 1963; Minifie, 1973; Tosi, 1979).

Acoustical characteristics differ for the consonant sounds. Nasal consonants have acoustic energy concentrated in the low frequencies. For stop consonants, spectra of the bursts associated with these sounds depend on the point of obstruction in the oral cavity for production of these sounds. Consequently, stops are characterized based on these frequency regions of energy concentration within the spectra (Handel, 1989; Perkins and Kent, 1986; Halle et al., 1957). Intensity and spectral characteristics differ among the fricatives. Spectral characteristics depend on the place of constriction in the oral cavity for production of these sounds. Resonant frequencies are higher when the constriction is closer to the lips. Additionally, the upper and lower frequency limits within the spectra vary among fricatives (Handel, 1989; Perkins and Kent, 1986; Minifie, 1973; Strevens, 1960).

Acoustical Methods

Numerous acoustical methods are used to examine the characteristics of speech sounds. Methods which are frequently used to study air-borne speech sounds include oscilloscopic analysis, FFT, and sound spectrography.

Oscilloscopic analysis

An oscilloscope analyzes pressure variations in speech sound waves over time (Denes and Pinson, 1963). The instrument produces an amplitude-time curve which is referred to as a waveform. For evaluating speech sounds, the shape of the waveform is examined, and the duration and amplitude of the wave are measured. Additionally, the frequency of the speech sound wave is estimated

(Cudahy, 1988; Small, 1973). An example of a waveform for the vowel speech sound /i/ is shown in Figure II.1.

A variety of waveforms is associated with speech sounds. Peterson and Shoup (1966) and Shoup and Pfeifer (1976) have classified the waveforms of speech sounds. The major types include the quiescent, burst, quasi-random, and quasi-periodic. Quiescent waveforms occur in the absence of sound and are associated with pauses in speech and the initial portions of stop consonants when air flow from the lungs is obstructed. Bursts are associated with stop consonants and are characterized by impulses which indicate transient sound sources. The impulse occurs with the abrupt onset of air flow after release of the obstruction used to produce the consonant. Quasi-random waveforms are associated with fricatives and are characterized by random amplitudes which indicate a frictional sound source or turbulent air flow. Vibrations of the vocal folds produce quasi-periodic waves which are associated with voiced speech sounds such as vowels.

Fast Fourier Transform

Fast Fourier Transform (FFT) is based on Fourier's theory which states that complex sounds, such as speech sounds, are composed of a combination of sinusoid waves differing in frequency, amplitude, and phase relationships. The procedure divides complex sounds, either periodic or aperiodic, into their sinusoid components (Cudahy, 1988; Denes and Pinson, 1963; Handel, 1989; Perkins and Kent, 1986)

For FFT, a spectrum analyzer is frequently used. The instrument consists of a series of bandpass filters and produces a spectrum which displays amplitude as a function of frequency for a particular instant in time. For spectra of speech sounds, peaks within the spectra represent the resonant or formant frequencies of the vocal tract (Denes and Pinson, 1963; Handel, 1989; Perkins and Kent, 1986). A spectrum for the vowel /i/ is shown in Figure II.1.

Sound spectrography

Sound spectrography, or spectrographic analysis, is based on FFT; however, the time-varying aspects of speech sounds also are examined with this method. Spectrographic analysis employs a sound spectrograph and produces spectrograms which are tridimensional recordings of frequency, amplitude, and time. The spectrogram consists of bandwidth filters for FFT. Although a number of bandwidths are available, bandwidths of 45 and 300 Hz are frequently used for analysis of speech sounds. A 45-Hz bandwidth permits a fine frequency analysis and produces a narrowband spectrogram. A 300-Hz bandwidth permits a fine time analysis and produces a wideband spectrogram (Denes and Pinson, 1963; Perkins and Kent, 1986; Tosi, 1979).

Examples of narrowband and wideband spectrograms for the vowel /i/, as in "beet", are shown in Figure II.2. For both, time is plotted along the horizontal axis, and frequency is plotted along the vertical axis. Amplitude is indicated by the darkness of the spectrographic patterns with amplitude increasing as darkness increases. Narrowband spectrograms display dark horizontal bars which represent the harmonic structure of periodic or voiced speech sounds, such as /i/.

Wideband spectrograms display the level of acoustic energy over time for a selected range of frequencies. For speech sounds, an 8000-Hz range of frequencies is most often used. Dark horizontal bands within spectrograms represent formants. Formants are numbered as F1, F2, . . ., FN from bottom to top of a spectrogram (Denes and Pinson, 1963; Perkins and Kent, 1986).

New generation spectrographs employ digital processing and operate in "real time". They produce waveforms, spectra, and spectrograms. FFT is performed on a time slice of a sound, and the duration of the time slice and the frequency range for analysis can be selected (Cudahy, 1988).

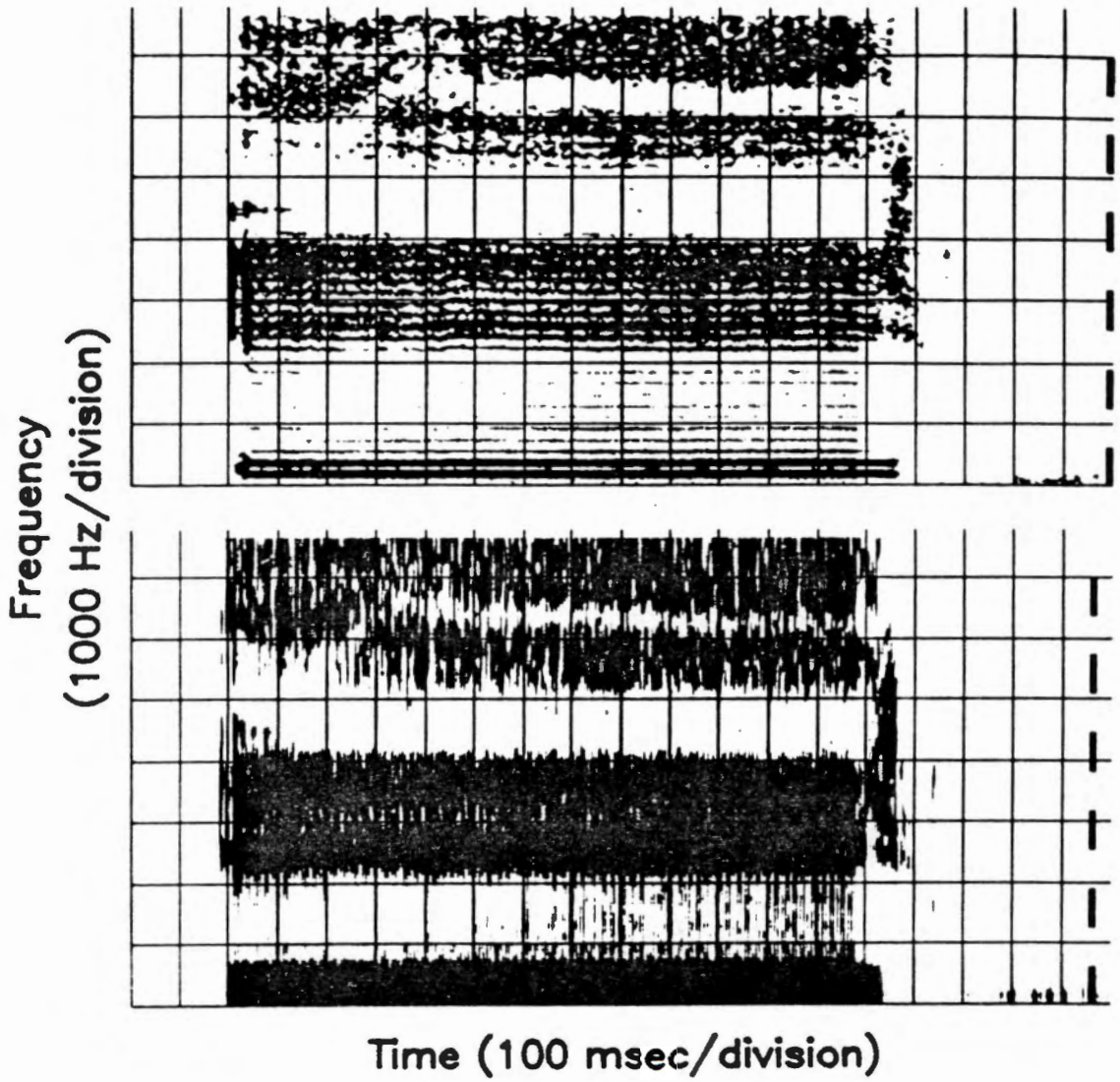


Figure II.2 – Narrowband spectrogram (top) and wideband spectrogram (bottom) for the vowel /i/ produced by an adult female. Time proceeds from left to right, and frequency increases from bottom to top of the spectrograms. Darkness of the spectrograms indicates amplitude with amplitude increasing as darkness increases.

5. MASTICATION IN RELATION TO FOOD TEXTURE

The masticatory act has been reviewed in a number of articles. These reviews indicate that the events which occur during mastication are relevant to the physical properties of food.

Masticatory Act

Kawamura (1964) and Boyar and Kilcast (1986b) explained that mastication is a complex physiological process in which food particles are selectively reduced in size and mixed with saliva. Movements of the mandible against the maxilla permit the teeth to cut, tear, grind, and crush food, thereby reducing particle size. The masseter and the temporal, internal, and external pterygoid muscles enable mandibular movements. These movements occur about the temporomandibular joints (TMJs). Because the TMJs are hinge-gliding joint, the mandible is capable of lateral movements and elevation, depression, protrusion, and retraction. Other anatomical structures of the oral cavity also function during mastication. Whereas the lips and cheeks keep food particles within the oral cavity, the tongue directs the particles to the surfaces of the teeth and mixes the bolus of food with saliva.

Yurkstas (1965) explained that mastication is a selective process in which large particles are reduced in size more rapidly than small particles. Lucas and Luke (1983) identified 2 aspects of mastication including the selection of food particles for breakdown and the breakage or fragmentation pattern of the particles. Olthoff et al. (1986) and Voon et al. (1986) indicated that the selection of particles depends on the number and size of the particles, manipulation of the particles within the oral cavity, and the size of the teeth relative to the size of the oral cavity. Breakage, however, depends on the shape of the teeth in contact with the food, the rate of force application, and the textural characteristics of the food.

Mandibular movements generate occlusal forces, biting and chewing forces, which act through the teeth for breakdown of food particles. Boyar and Kilcast (1986b) reported that the magnitude of these forces depends on the region of the oral cavity. The researchers explained that teeth in the posterior region of the cavity exert forces larger in magnitude than teeth in the anterior region of the cavity. Differences in magnitude are attributed to the proximity of the teeth to the TMJs. Teeth in the posterior region are closer to the joint than teeth in the anterior region; therefore, they travel a shorter distance and at a slower speed. The researchers indicated that magnitude of the forces at the incisors is 25-33% of that at the molars.

Bourne (1977) reported variables that affect the rate of mastication. The researcher found variations among individuals who masticated chewing gum. The number of chews per min were counted after adult males and females masticated the gum to a "steady state." Rates ranged from 26 to 132 chews/min. Bourne (1977) also reported that chewing rates decrease as the toughness of foods increases. Furthermore, the researcher explained that for hard foods the first chews are slow as force is steadily applied to crack the food. Rates increase once the food is broken down and mixed with saliva. Harrington and Pearson (1962) found that "chew counts" varied for 6 subjects who chewed samples of pork chops. The mean number of chews needed to prepare a sample for swallowing ranged from 25.3 to 47.0 chews.

Food Texture

For evaluation of food texture, food scientists have constructed instruments fitted with dentures to simulate the action of the mouth during mastication. The Bite Tenderometer and the strain-gauge Denture Tenderometer were the two major efforts.

Volodkevich (1938) constructed the Bite Tenderometer from a pair of squeeze jaws for evaluation of meat tenderness. The jaws moved in a manner opposite that of the human jaw to produce

force-deformation curves. Specifically, the upper jaw moved relative to the lower jaw. Two types of attachments were tested including a set of dentures and 2 wedges with rounded edges. The researcher found that the attachments produced different curves for samples of boiled beef. Whereas curves for the dentures had 2 peaks, curves for the wedges had 1 peak. Additionally, resistance of the meat samples to the dentures was twice as great as that to the wedges. The researcher attributed these results to adhesion of the meat to the dentures.

Proctor et al. (1955, 1956a) constructed the strain-gauge Denture Tenderometer to evaluate the tenderness of foods. The instrument consisted of a masticator which was a set of plastic dentures attached to a modified dental articulator. The articulator simulated the vertical, lateral, and forward movements of the human jaw; however, the upper jaw moved relative to the lower jaw. Resilient plastic material surrounded the masticator to simulate the actions of the lips, cheeks, and tongue. Strain gauges were attached to the vertical movement beam, and resistance to chewing was registered as strain which was converted to resistance by the gauge. The output of the gauge was amplified and sent to an oscilloscope which plotted force-penetration measurements throughout the chewing cycle.

Proctor et al. (1956b) examined the validity of the Denture Tenderometer. Measurements from the Denture Tenderometer for tenderness of fresh, frozen, and canned peas were correlated with those from sensory evaluation and from the Canco Tenderometer, an instrument for measurement of pea tenderness. Results indicated high correlations for the 2 types of tenderometers ($r=0.99$) and for the denture tenderometer and sensory evaluation scores for tenderness ($r=0.96$). Despite the high correlations, the researchers indicated the disadvantage of the instrument. They pointed out that the instrument did not include the effects of saliva. However, they added that the principles of the instrument could be used for the design of more practical instruments.

Consequently, the Denture Tenderometer served as a prototype for the General Foods Texturometer (Friedman et al., 1963).

Recently, researchers have examined other methods for evaluating food texture during mastication. Tornberg et al. (1985) studied the masticatory patterns for meats and meat products including whole meats, hamburgers, sausages, and restructured beef. For evaluation, strain gauges were attached to an intraoral prosthetic devices which was fitted to the maxillary bridge of a 63-year old subject. The output of the strain gauges was sent to an oscilloscope for measurement of maximum force, chew cycle time, and the total number of chewing cycles needed to prepare samples for swallowing. Results indicated that maximum force decreased as the degree of comminution of the meats increased. Chew cycle time varied from 0.7 to 0.95 sec, but no significant differences were found among the meat samples. Total number of chewing cycles varied from 20 to 70 cycles; however, this measure correlated with subjective estimates of toughness, juiciness, and the amount of residue in the mouth.

Boyar and Kilcast (1986a) investigated the motor responses of the masseter muscle during mastication. Electromyography (EMG), which senses electrical potentials, was used to measure these responses. EMG recordings were obtained for 2 subjects who chewed samples of a gelatin-based jelly and a carrageenan gel. The researchers found that similar forces were needed to break the gel and the jelly on the first bite. However, larger forces were needed to break down the gel than the jelly after the first bite. Amemiya (1990) and Eves et al. (1990) also have studied EMG as a method for evaluating the forces needed to break down gum-based confectionary products.

Review of these studies indicates that food scientists are interested in developing methods to evaluate texture during mastication. Currently, researchers are advocating collaborative research in this endeavor (Boyar and Kilcast, 1986b; Heath and Lucas, 1987; Hutchings and Lillford, 1988).

CHAPTER III

SOUND SPECTROGRAPHY AS A METHOD FOR EVALUATING MASTICATION SOUNDS: A PRELIMINARY INVESTIGATION

1. INTRODUCTION

Recently, interest in the evaluation of food texture during mastication has increased (Amemiya, 1990; Boyar and Kilcast, 1986a; Eves et al., 1990; Hutchings and Lillford, 1988). Researchers have suggested that analysis of mastication sounds may provide information concerning texture and have studied the spectra, intensities, and noise bursts of these sounds (Drake, 1963, 1965a; Edmister and Vickers, 1985; Lee et al., 1988, 1990; Vickers, 1984b, 1987; Vickers and Bourne, 1976). However, information is lacking for the acoustical characteristics of mastication sounds. Drake (1965b) used a "visible speech" technique (sound spectrography) to study the frequency-amplitude-time characteristics of mastication sounds. The researcher stated that this technique could be developed to provide information for the characteristics and that it could be used to determine conditions for other types of analyses.

Sound spectrography, or spectrographic analysis, permits evaluation of the time-varying aspects of speech sounds. In particular, changes in the spectral characteristics are examined (Perkins and Kent, 1986; Tosi, 1979). The method employs a sound spectrograph and is based on Fast Fourier Transformation (FFT) which partitions complex sounds into their sinusoid components. New generation spectrographs, which employ digital processing, operate in "real time" and produce waveforms, spectra, and spectrograms (Cudahy, 1988).

In this experiment, sound spectrography was applied to mastication sounds of 10 food samples differing in textural properties. Mastication sounds for 3 subjects were evaluated. The objectives of the experiment were as follows: to use a digital sound spectrograph to generate waveforms and wideband spectrograms of

mastication sounds for the initial chews of the food samples; to describe acoustical characteristics of the sounds from the waveforms and spectrograms; and to compare characteristics of the sounds for the food samples and subjects.

2. MATERIALS AND METHODS

Subjects

Three subjects produced the sounds which were recorded and evaluated in the experiment. Subjects were from 19 to 27 years of age and were students in the Department of Food Technology and Science at The University of Tennessee, Knoxville. Throughout this chapter, subjects are referred to as subject 1 (male), subject 2 (female), and subject 3 (female).

Food Samples

Mastication sounds were recorded and evaluated for the 10 food samples listed in Table III.1. The first 7 samples are reference standards for the fracturability and hardness scales of the Texture Profile Method (Muñoz, 1986; Szczesniak et al., 1963). Sizes of the samples were those indicated for the method. These samples were selected for study because the objective of the experiment was to evaluate sounds for foods differing in textural properties. All samples were room temperature (approximately 20^{o}C). For each subject, sounds for 2 sets of the samples were recorded. All recording was done on the same day.

Recording

Subjects were seated in a sound treated booth to reduce the level of environmental noise during recording. For production of the mastication sounds, subjects chewed the food samples with the molar teeth. This technique was used because it is the technique for

Table III.1 – Type, brand, and size of food samples[a]

Food	Type; brand	Sample size
Graham cracker	Regular; Nabisco Brands	1.27-cm square
Melba toast	White; Old London	1.27-cm square
Ginger snap	Old fashion; Nabisco Brands	1.27-cm square
Peanut	Roasted, lightly salted; Eagle Brand Snacks, Inc.	1 nut
Almond	Roasted, salted; Blue Diamond	1 nut
Carrot	Raw	1.27-cm slice
Hard candy	Life Saver; Nabisco Brands	1 piece
Celery	Raw, outer rib	1.27-cm slice
Malted milk ball	Whoppers; Leaf, Inc.	1 ball
Corn snack	Planters Cheez Ball; Nabisco Brands	1 ball

[a]Samples were room temperature (approximately 20°C).

sensory evaluation of hardness for the Texture Profile Method (Muñoz, 1986; Szczesniak et al., 1963). Additionally, subjects chewed the samples with their mouths open to maximally capture sounds for recording.

The recording system consisted of the following: 2.54-cm condenser microphone (Bruel and Kjaer Instruments, Inc., Denmark); 1.27-cm preamplifier (element 2619, Bruel and Kjaer Instruments, Inc., Denmark); microphone power supply (model 2807, Bruel and Kjaer Instruments, Inc., Denmark); and tape recorder (model TC-377, Sony, Japan). For recording, the microphone was positioned 6 cm from the mouths of the subjects. Sounds were recorded on 0.635-cm audio-magnetic tape (Scotch Brand, 3M, St. Paul, MN) with the tape recorder operated at a speed of 19 cm/sec. All mastication sounds were recorded at a level ranging from -7 to +1 dB in reference to the volume unit (VU) meter of the tape recorder.

Acoustical Analysis

The following system was used for acoustical analysis of the recorded sounds: tape recorder (model RT-1011L, Pioneer Electronics Corp., Japan); digital sound spectrograph (DSP Sona-Graph, model 5500, Kay Elemetrics Corp., Pine Brook, NJ); and gray scale printer (model 5510, Kay Elemetrics Corp., Pine Brook, NJ). The tape recorder was operated at a speed of 19 cm/sec. For comparison of amplitude of the mastication sounds, the playback level of the recorder and the input level of the spectrograph were held constant for analysis of all sounds.

The spectrograph generated waveforms (amplitude-time plots) and wideband spectrograms (frequency-amplitude-time plots) for the sounds of the initial chews of the food samples. For the spectrograms, standard procedures for wideband spectrograms of speech sounds were used (Perkins and Kent, 1986; Tosi, 1979). Procedures included using a 100-point transform size for FFT, a frequency range of 0-8000 Hz for analysis, and high frequency input shaping (high shaping). High shaping placed a 6 dB/octave emphasis on frequencies greater than

1000 Hz. This emphasis permitted evaluation of formants at these frequencies.

The following acoustical characteristics were described from waveforms and wideband spectrograms of sounds for the initial chews of the food samples: duration of the sounds; amplitude of the sounds; distribution of acoustic energy over the frequency range of 0-8000 Hz; and formants. Distribution of acoustic energy was described as either bursts or continuous. Bursts appeared as sharp peaks in the sound waves for the chews. For a continuous distribution, bursts were absent and acoustic energy was continuous for the duration of each chew.

Formants are spectral characteristics of vowels sounds. For wideband spectrograms, formants appear as dark horizontal bands in the patterns of vowel sounds. Because darkness of a spectrogram indicates amplitude, these bands indicate frequency regions of high amplitude within the spectrogram. Approximately 4 or 5 formants are associated with a particular vowel and are numbered as F1, F2, . . ., FN from bottom to top of a spectrogram (Denes and Pinson, 1963; Perkins and Kent, 1986; Tosi, 1979). Formants for the vowel sound /i/ are shown in the wideband spectrogram in Figure II.2.

Dark horizontal bands appeared on the wideband spectrograms of mastication sounds. In keeping with the terminology for speech sounds, the model for this study, these bands were referred to as formants and were numbered accordingly. The number of formants for the initial chews of the food samples and the range of frequencies over which the formants occurred were described and compared for sounds of the different food samples and subjects.

The waveforms and spectrograms of the mastication sounds also were evaluated by the following members of the Department of Audiology and Speech Pathology at The University of Tennessee, Knoxville: Dr. C.W. Asp; Dr. A.K. Nabelek; Dr. I.V. Nabelek; and Y. Takata. These individuals are experienced in spectrographic analysis of speech sounds.

3. RESULTS AND DISCUSSION

Waveforms and corresponding wideband spectrograms of mastication sounds for the food samples are shown in Figures III.1-III.16. For comparison of sounds for the 10 food samples, waveforms and spectrograms of sounds produced by subject 1 (adult male) for all samples are shown in Figures III.1-III.10. For comparison of sounds for the subjects, waveforms and spectrograms of sounds for selected food samples are shown for subjects 2 and 3 (adult females) in Figures III.11-III.13 and III.14-III.16, respectively.

Waveforms and wideband spectrograms show sounds for the initial 3-8 chews over a 4-sec interval (200 msec/vertical division). Time proceeds from left to right. Specifically, waveforms display amplitude (voltage) over time for the sounds. Spectrograms display the level of acoustic energy over time for the initial 8000-Hz range of frequencies (1000 Hz/horizontal division). Frequency increases from bottom (0 Hz) to top (8000 Hz) of the spectrograms. Darkness of the spectrographic pattern indicates amplitude with amplitude increasing as darkness increases.

Duration of Mastication Sounds

Durations of sounds for the initial chews of the food samples were compared. Examination of waveforms and wideband spectrograms of sounds produced by subject 1 (Figures III.1-III.10) indicated differences in the durations of the sounds for the 10 food samples. Durations of the sounds for the graham cracker (Figure III.1) and peanut (Figure III.4) were shorter than those for the sounds of the other food samples. A long duration characterized sounds for successive chews of the ginger snap (Figure III.3), hard candy (Figure III.7), celery (Figure III.8), and corn snack (Figure III.10). In contrast, duration decreased for sounds of successive chews of the melba toast (Figure III.2), almond (Figure III.5), raw carrot (Figure III.6), and malted milk ball (Figure III.9).

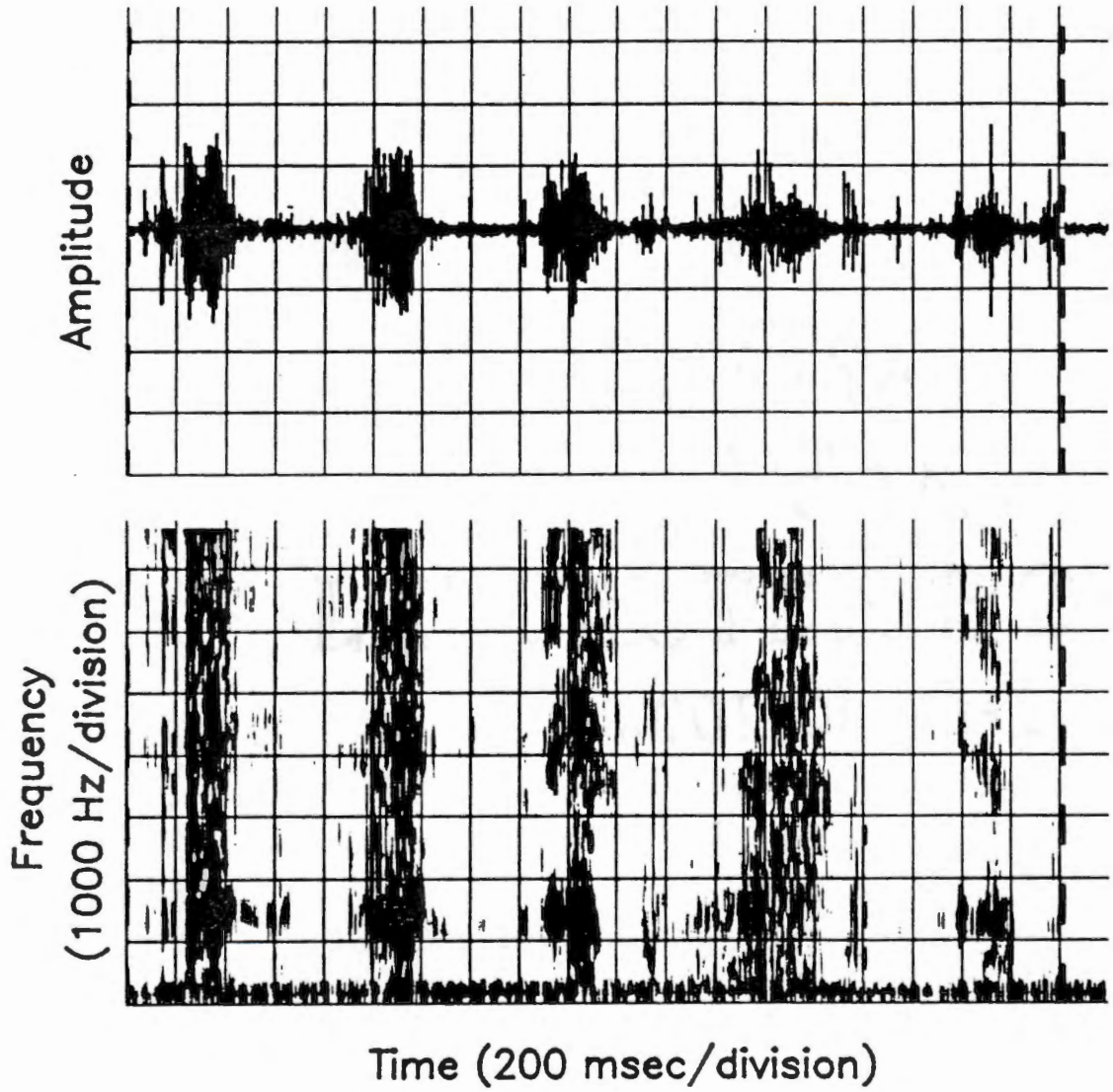


Figure III.1 – Waveform (top) and corresponding wideband spectrogram (bottom) of the sounds for the initial 5 chews of a graham cracker by subject 1 (adult male). Time proceeds from 0 to 4 sec from left to right. Frequency increases from 0 to 8000 Hz from bottom to top of the spectrogram. Darkness of the spectrogram indicates amplitude with amplitude increasing as darkness increases.

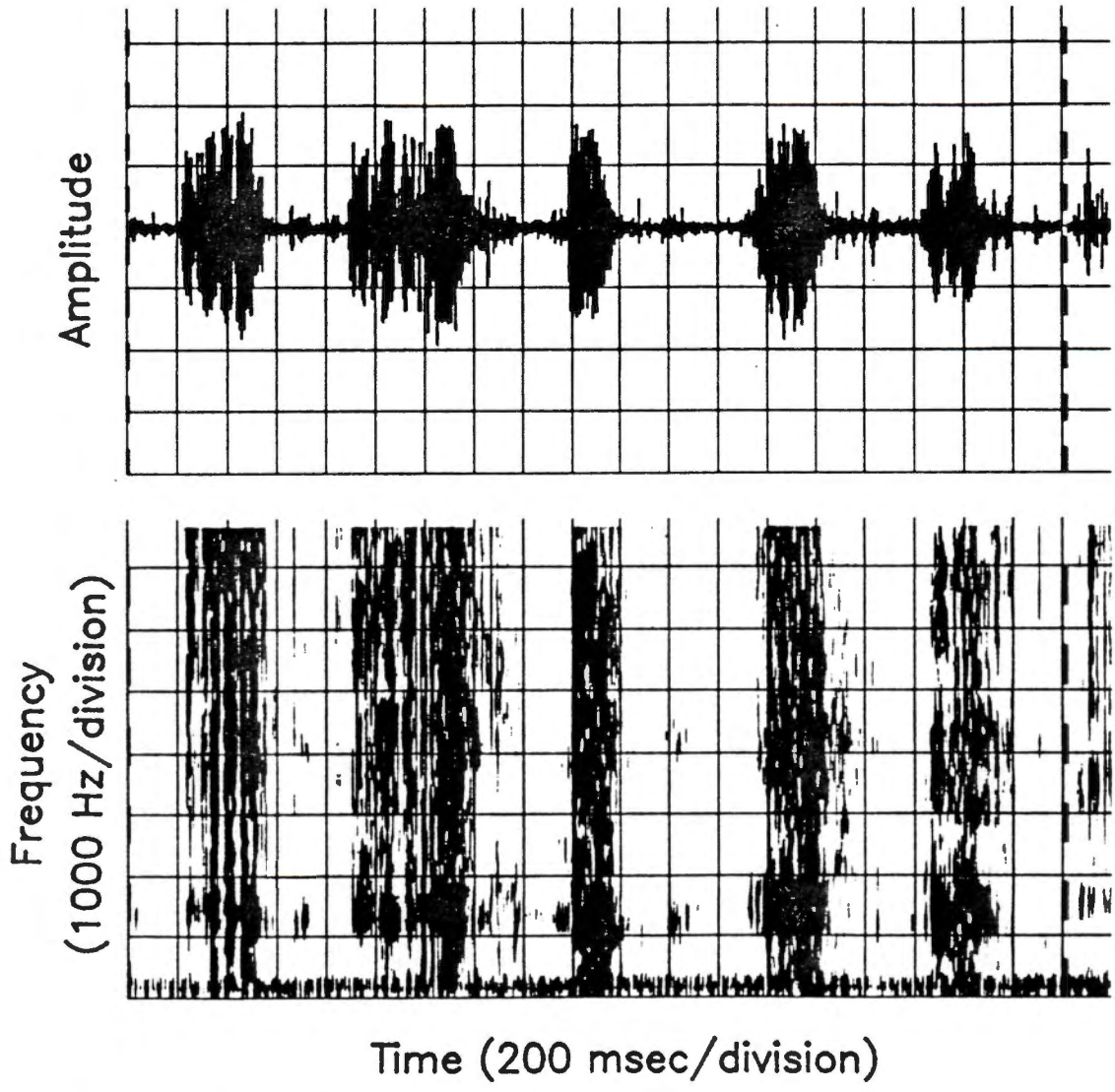


Figure III.2 – Waveform (top) and corresponding wideband spectrogram (bottom) of the sounds for the initial 5 chews of melba toast by subject 1 (adult male). Time proceeds from 0 to 4 sec from left to right. Frequency increases from 0 to 8000 Hz from bottom to top of the spectrogram. Darkness of the spectrogram indicates amplitude with amplitude increasing as darkness increases.

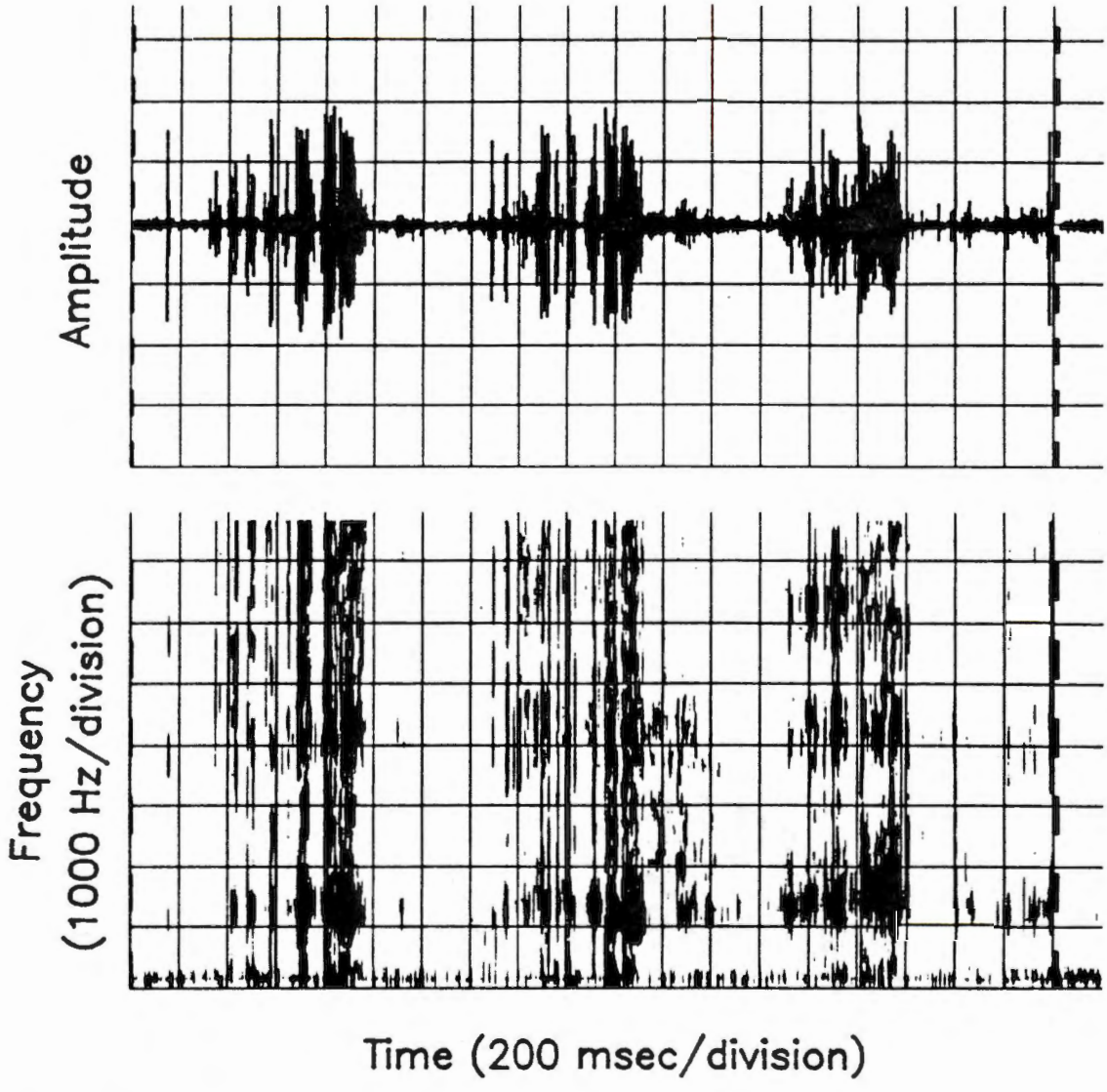


Figure III.3 – Waveform (top) and corresponding wideband spectrogram (bottom) of the sounds for the initial 3 chews of a ginger snap by subject 1 (adult male). Time proceeds from 0 to 4 sec from left to right. Frequency increases from 0 to 8000 Hz from bottom to top of the spectrogram. Darkness of the spectrogram indicates amplitude with amplitude increasing as darkness increases.

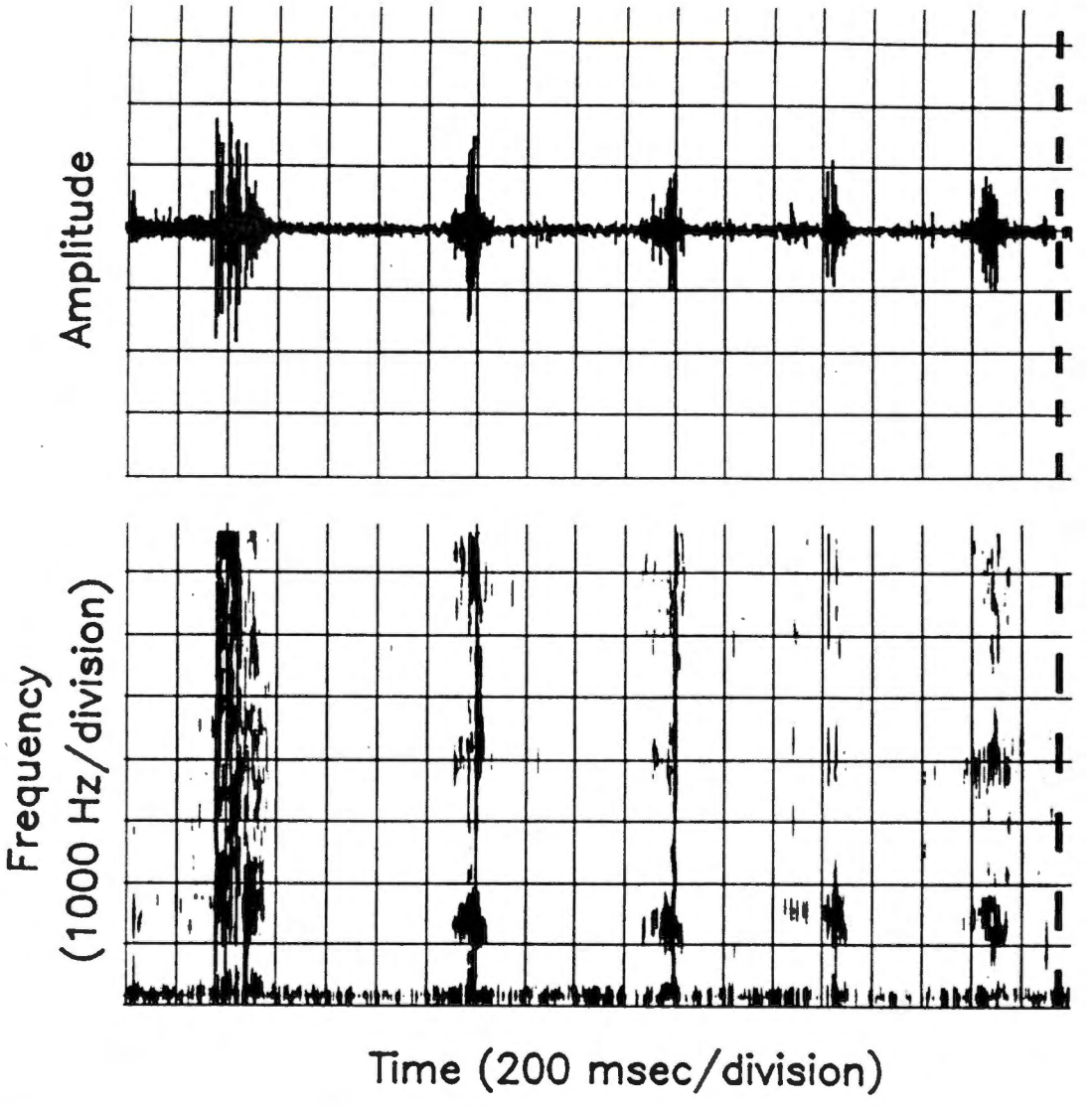


Figure III.4 – Waveform (top) and corresponding wideband spectrogram (bottom) of the sounds for the initial 5 chews of a peanut by subject 1 (adult male). Time proceeds from 0 to 4 sec from left to right. Frequency increases from 0 to 8000 Hz from bottom to top of the spectrogram. Darkness of the spectrogram indicates amplitude with amplitude increasing as darkness increases.

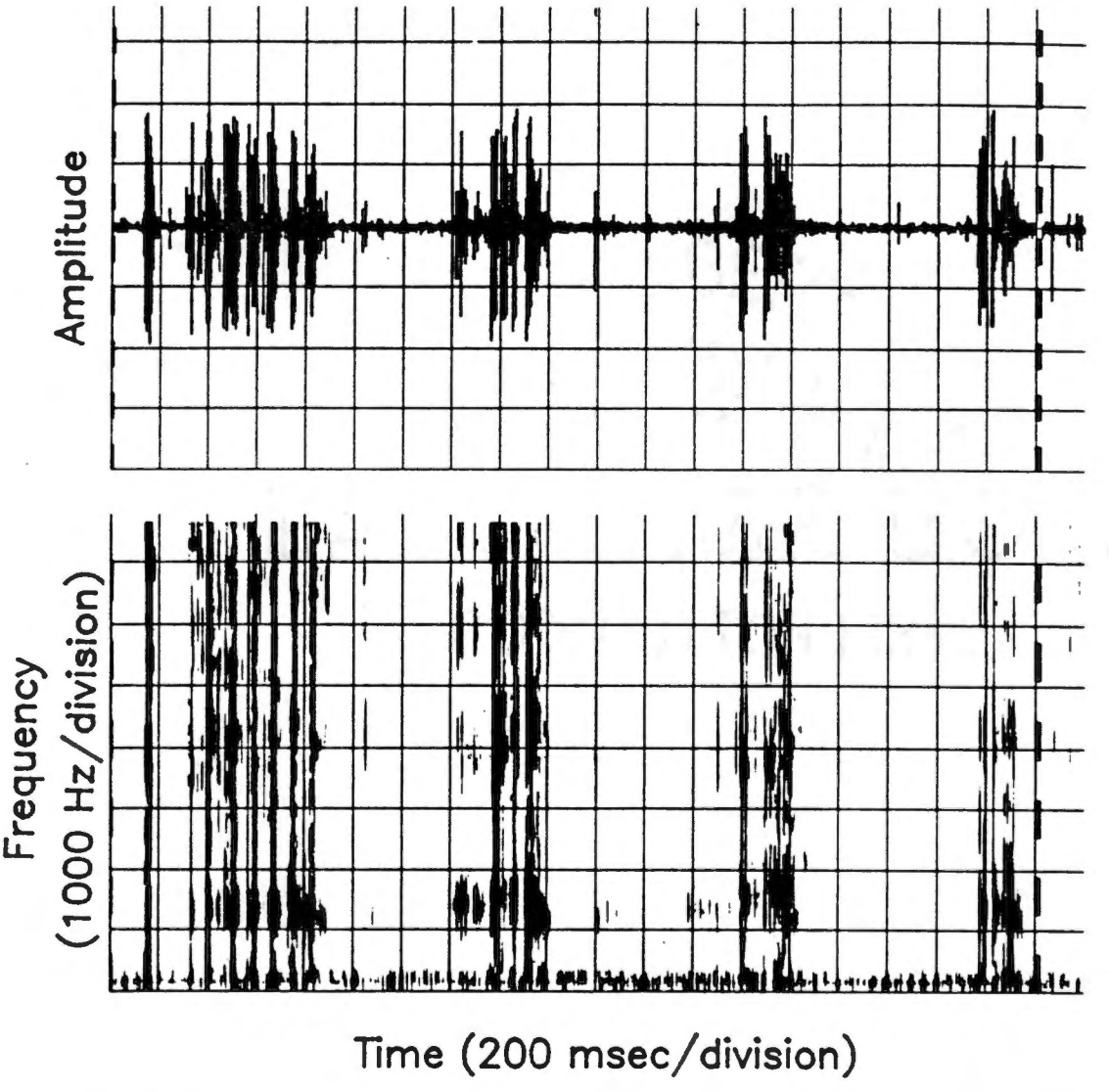


Figure III.5 – Waveform (top) and corresponding wideband spectrogram (bottom) of the sounds for the initial 4 chews of an almond by subject 1 (adult male). Time proceeds from 0 to 4 sec from left to right. Frequency increases from 0 to 8000 Hz from bottom to top of the spectrogram. Darkness of the spectrogram indicates amplitude with amplitude increasing as darkness increases.

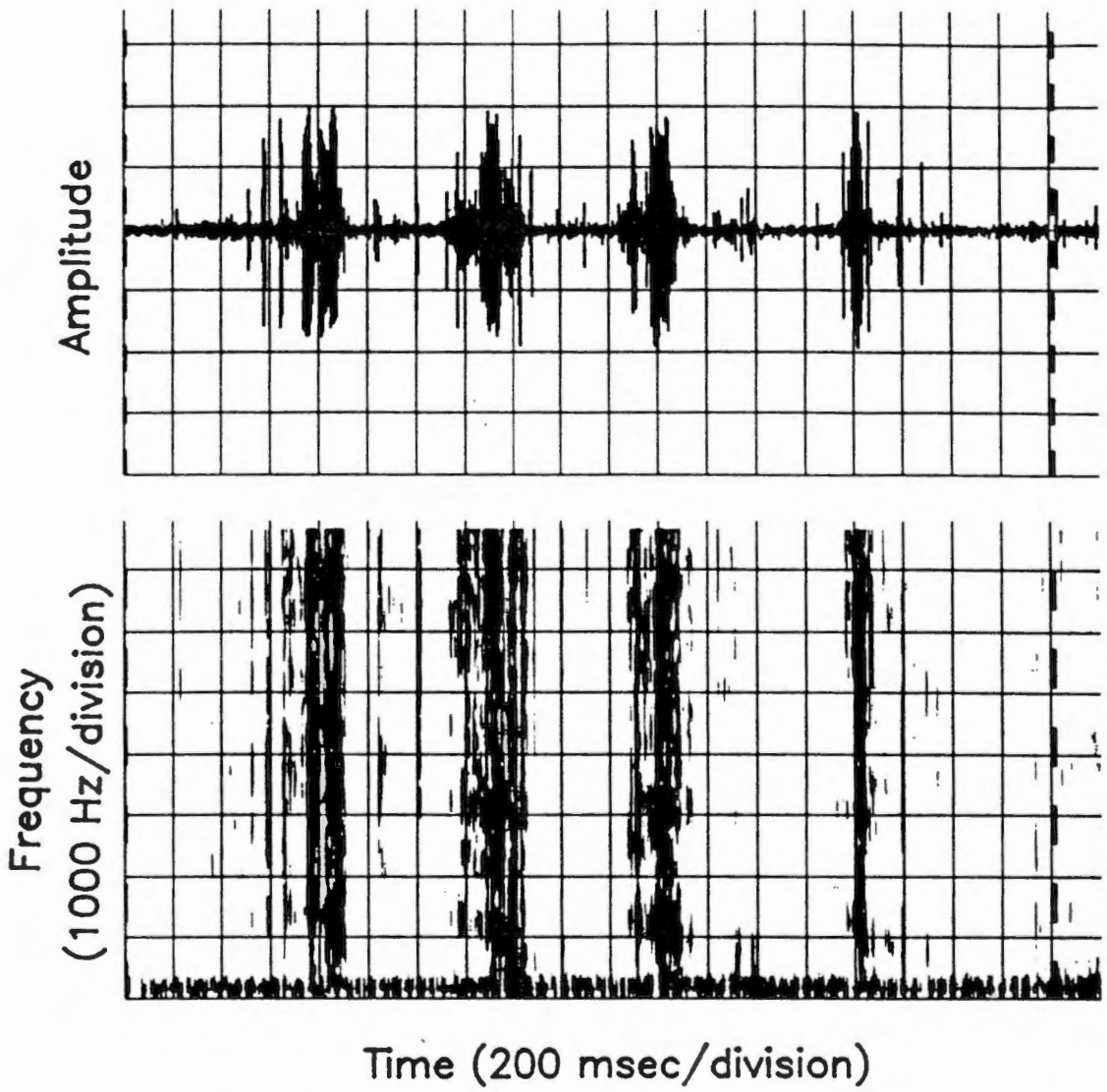


Figure III.6 – Waveform (top) and corresponding wideband spectrogram (bottom) of the sounds for the initial 4 chews of a carrot by subject 1 (adult male). Time proceeds from 0 to 4 sec from left to right. Frequency increases from 0 to 8000 Hz from bottom to top of the spectrogram. Darkness of the spectrogram indicates amplitude with amplitude increasing as darkness increases.

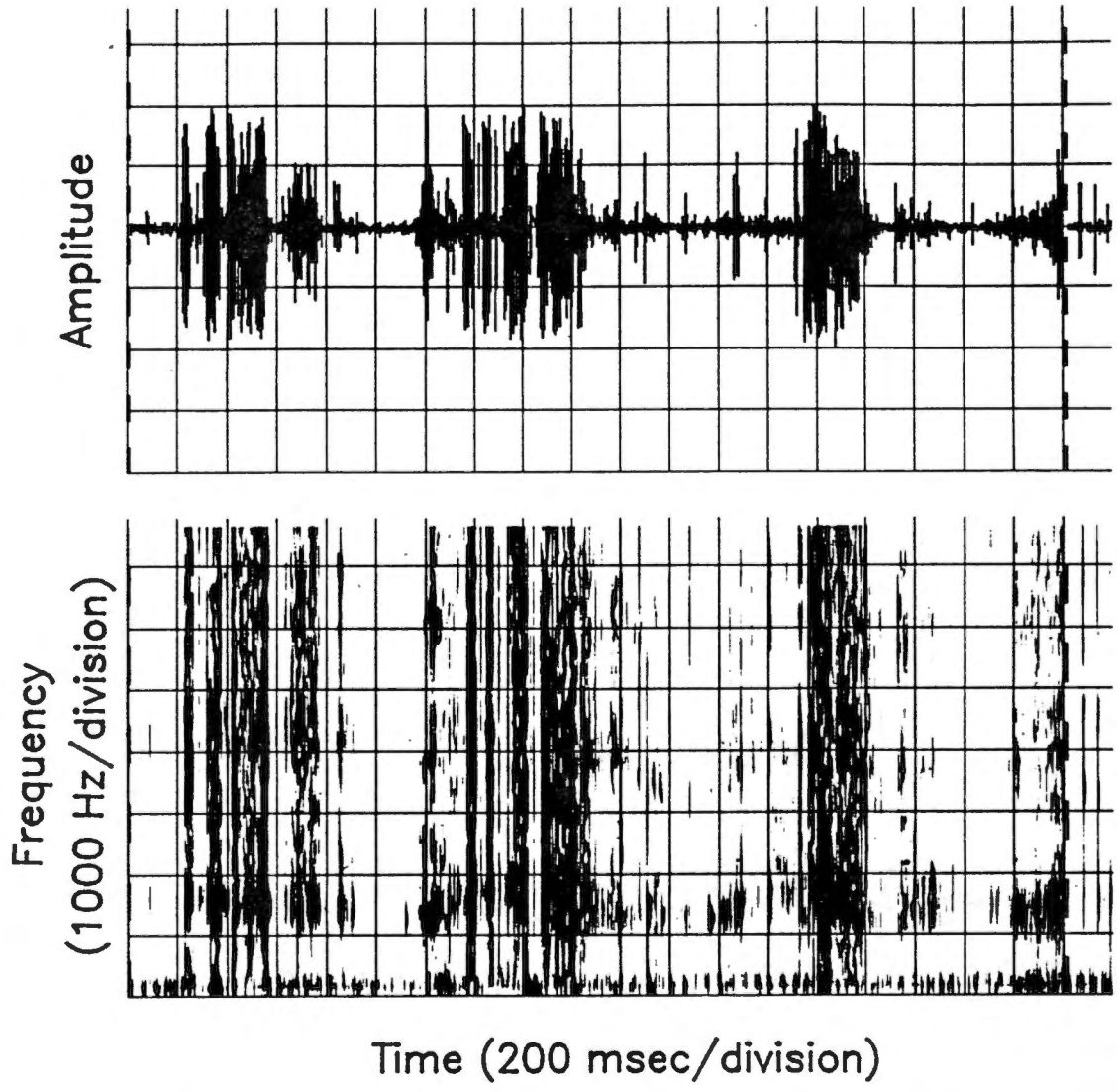


Figure III.7 – Waveform (top) and corresponding wideband spectrogram (bottom) of the sounds for the initial 3 chews of hard candy by subject 1 (adult male). Time proceeds from 0 to 4 sec from left to right. Frequency increases from 0 to 8000 Hz from bottom to top of the spectrogram. Darkness of the spectrogram indicates amplitude with amplitude increasing as darkness increases.

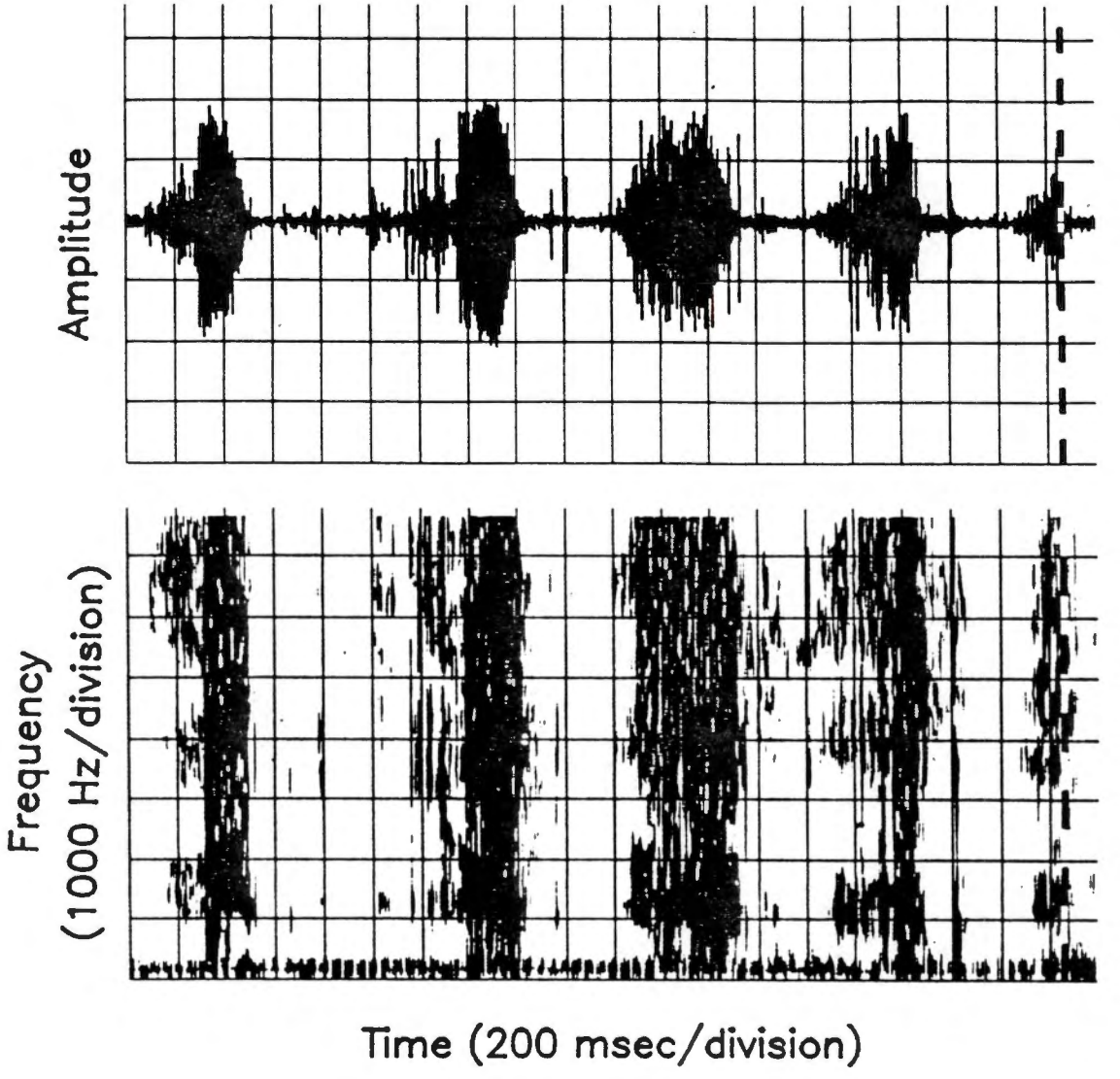


Figure III.8 – Waveform (top) and corresponding wideband spectrogram (bottom) of the sounds for the initial 4 chews of celery by subject 1 (adult male). Time proceeds from 0 to 4 sec from left to right. Frequency increases from 0 to 8000 Hz from bottom to top of the spectrogram. Darkness of the spectrogram indicates amplitude with amplitude increasing as darkness increases.

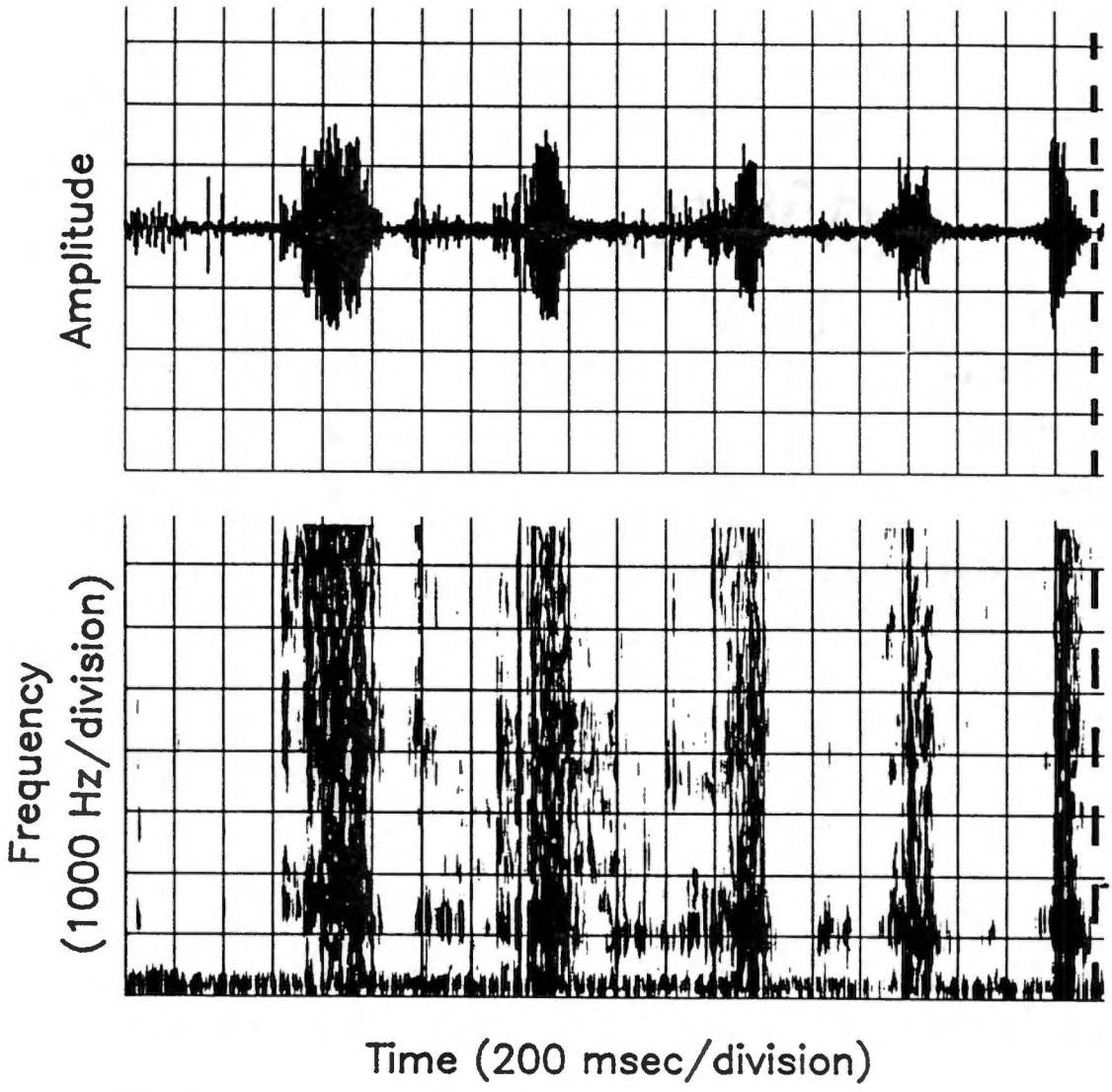


Figure III.9 – Waveform (top) and corresponding wideband spectrogram (bottom) of the sounds for the initial 5 chews of malted milk ball by subject 1 (adult male). Time proceeds from 0 to 4 sec from left to right. Frequency increases from 0 to 8000 Hz from bottom to top of the spectrogram. Darkness of the spectrogram indicates amplitude with amplitude increasing as darkness increases.

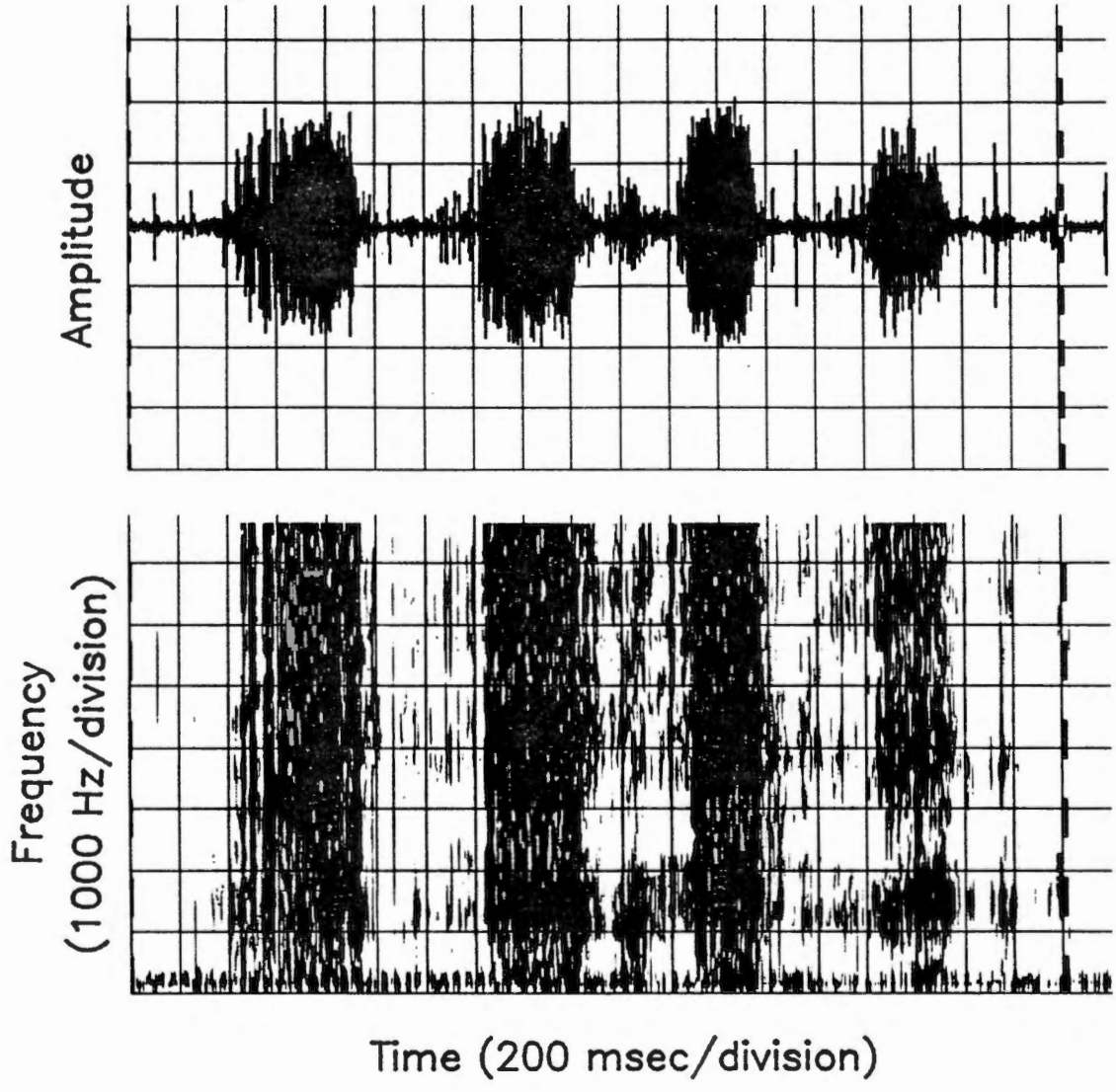


Figure III.10 – Waveform (top) and corresponding wideband spectrogram (bottom) of the sounds for the initial 4 chews of a corn snack by subject 1 (adult male). Time proceeds from 0 to 4 sec from left to right. Frequency increases from 0 to 8000 Hz from bottom to top of the spectrogram. Darkness of the spectrogram indicates amplitude with amplitude increasing as darkness increases.

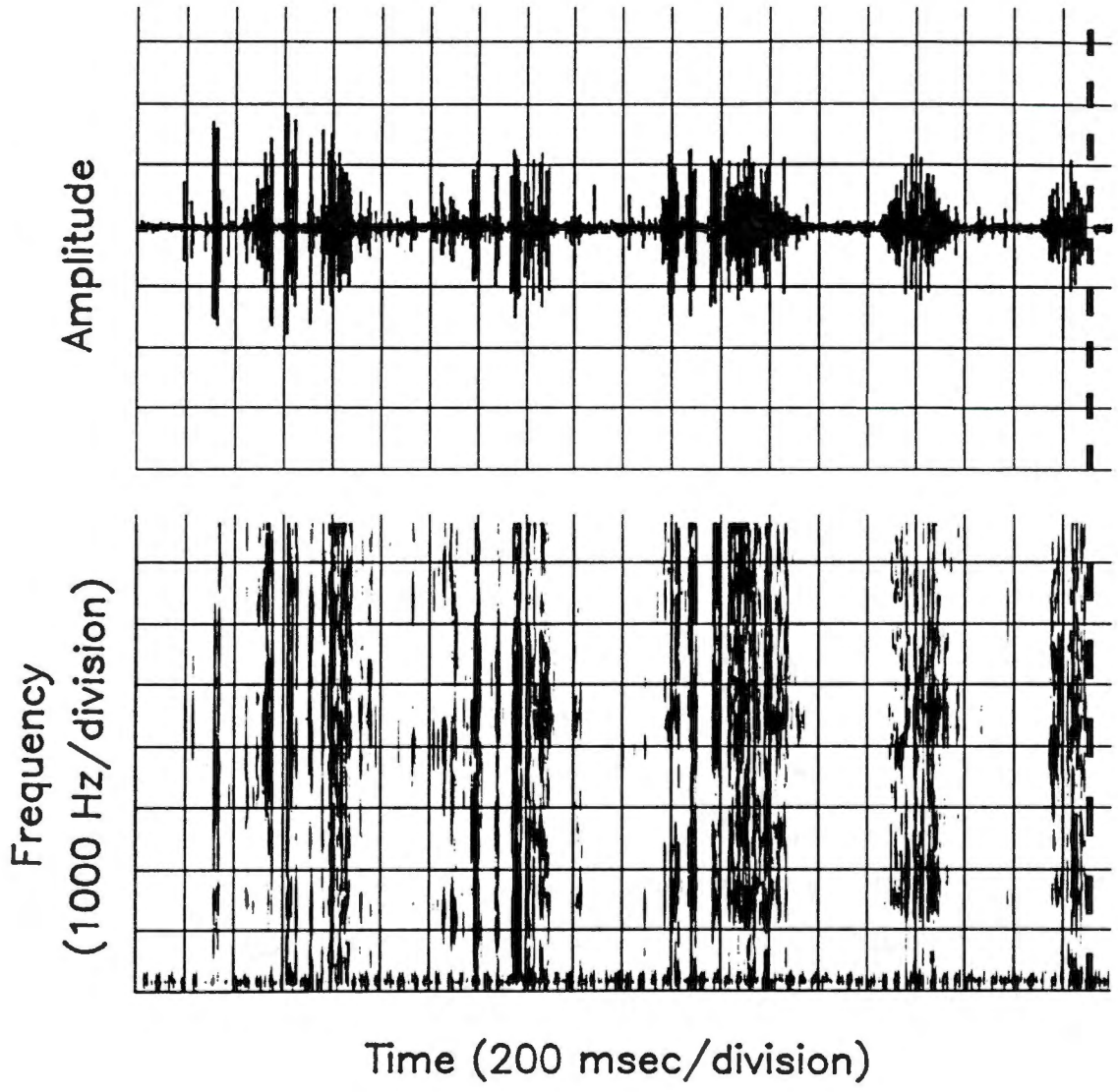


Figure III.11 – Waveform (top) and corresponding wideband spectrogram (bottom) of the sounds for the initial 5 chews of melba toast by subject 2 (adult female). Time proceeds from 0 to 4 sec from left to right. Frequency increases from 0 to 8000 Hz from bottom to top of the spectrogram. Darkness of the spectrogram indicates amplitude with amplitude increasing as darkness increases.

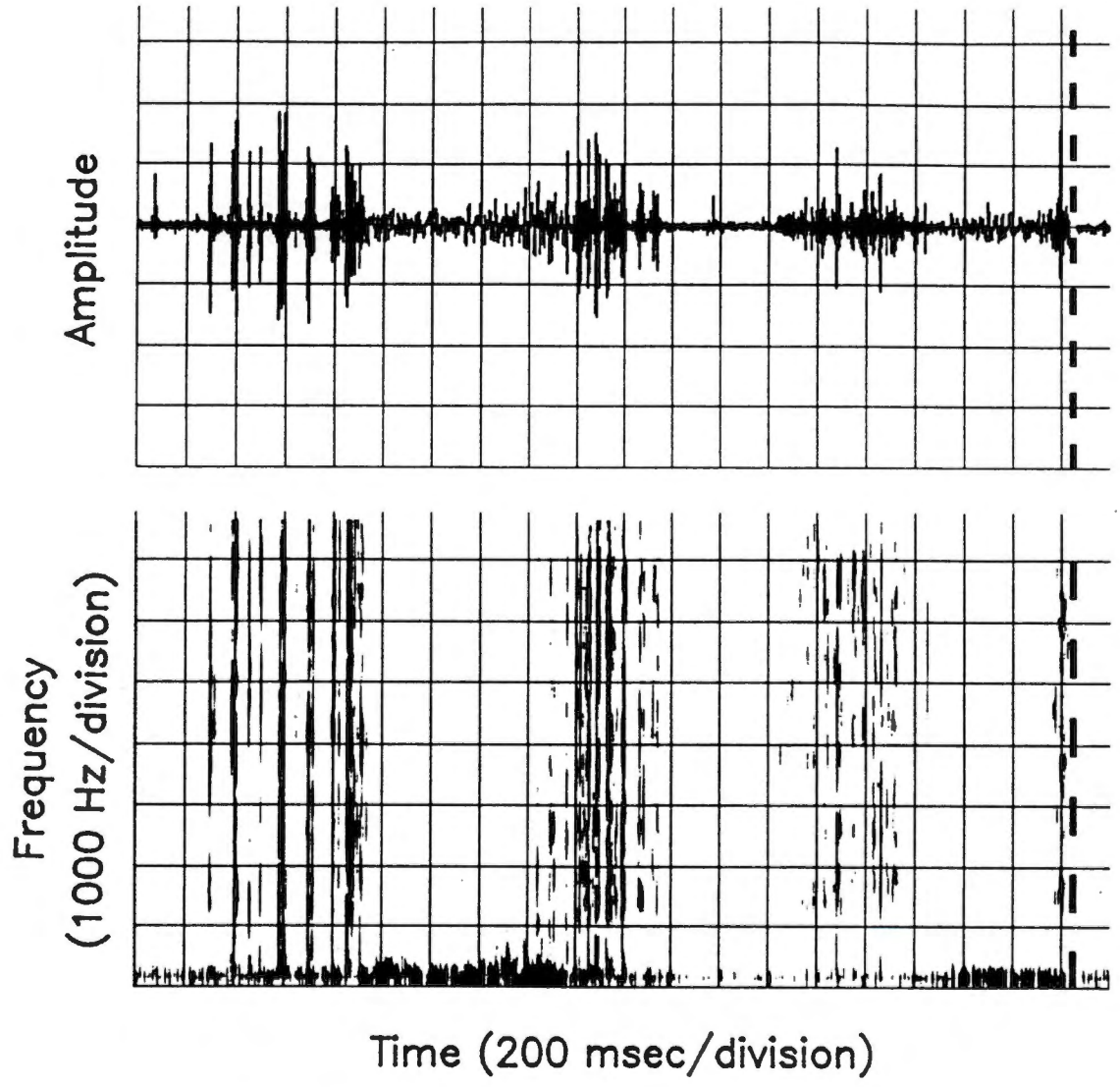


Figure III.12 – Waveform (top) and corresponding wideband spectrogram (bottom) of the sounds for the initial 3 chews of a ginger snap by subject 2 (adult female). Time proceeds from 0 to 4 sec from left to right. Frequency increases from 0 to 8000 Hz from bottom to top of the spectrogram. Darkness of the spectrogram indicates amplitude with amplitude increasing as darkness increases.

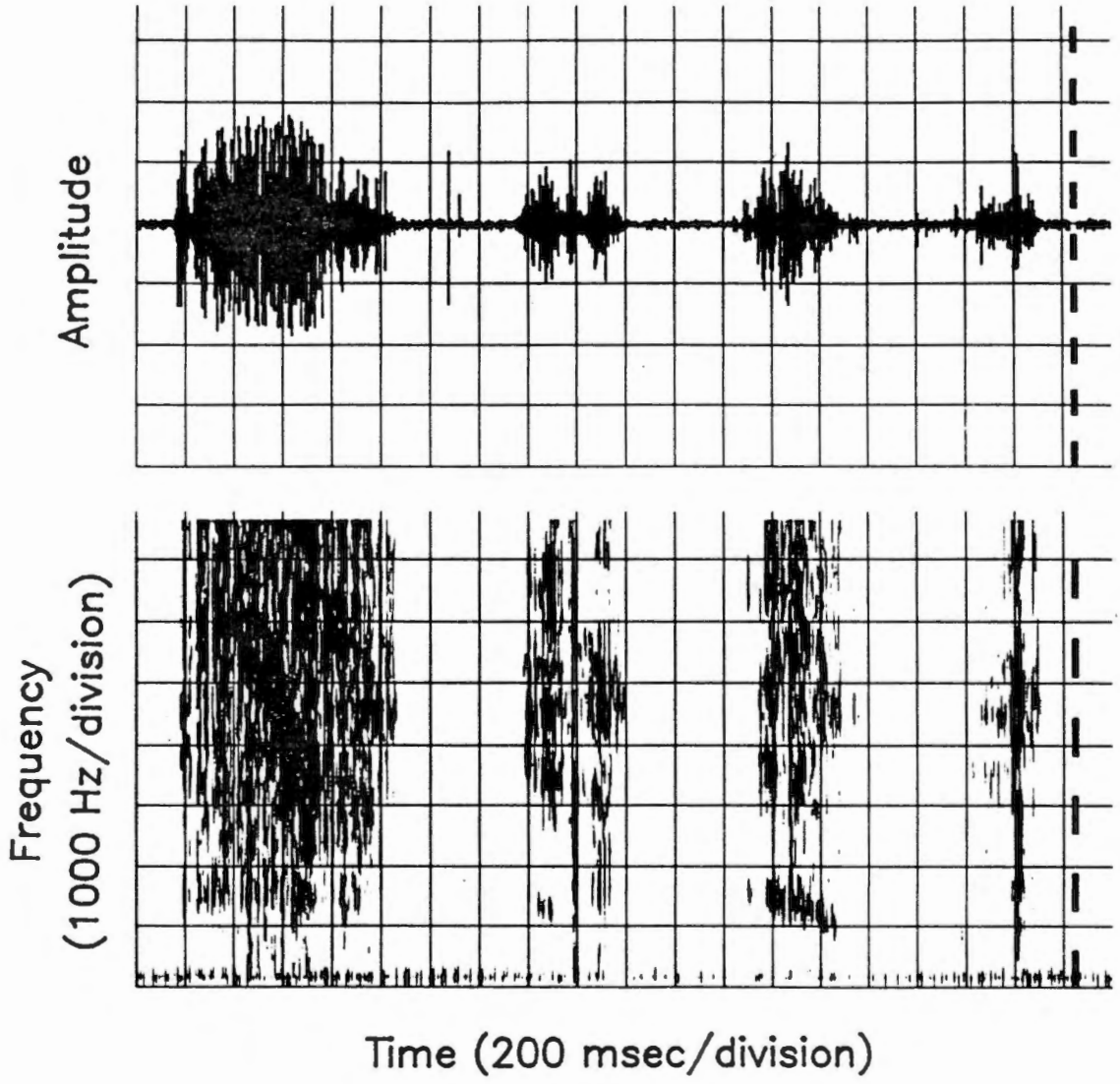


Figure III.13 – Waveform (top) and corresponding wideband spectrogram (bottom) of the sounds for the initial 4 chews of celery by subject 2 (adult female). Time proceeds from 0 to 4 sec from left to right. Frequency increases from 0 to 8000 Hz from bottom to top of the spectrogram. Darkness of the spectrogram indicates amplitude with amplitude increasing as darkness increases.

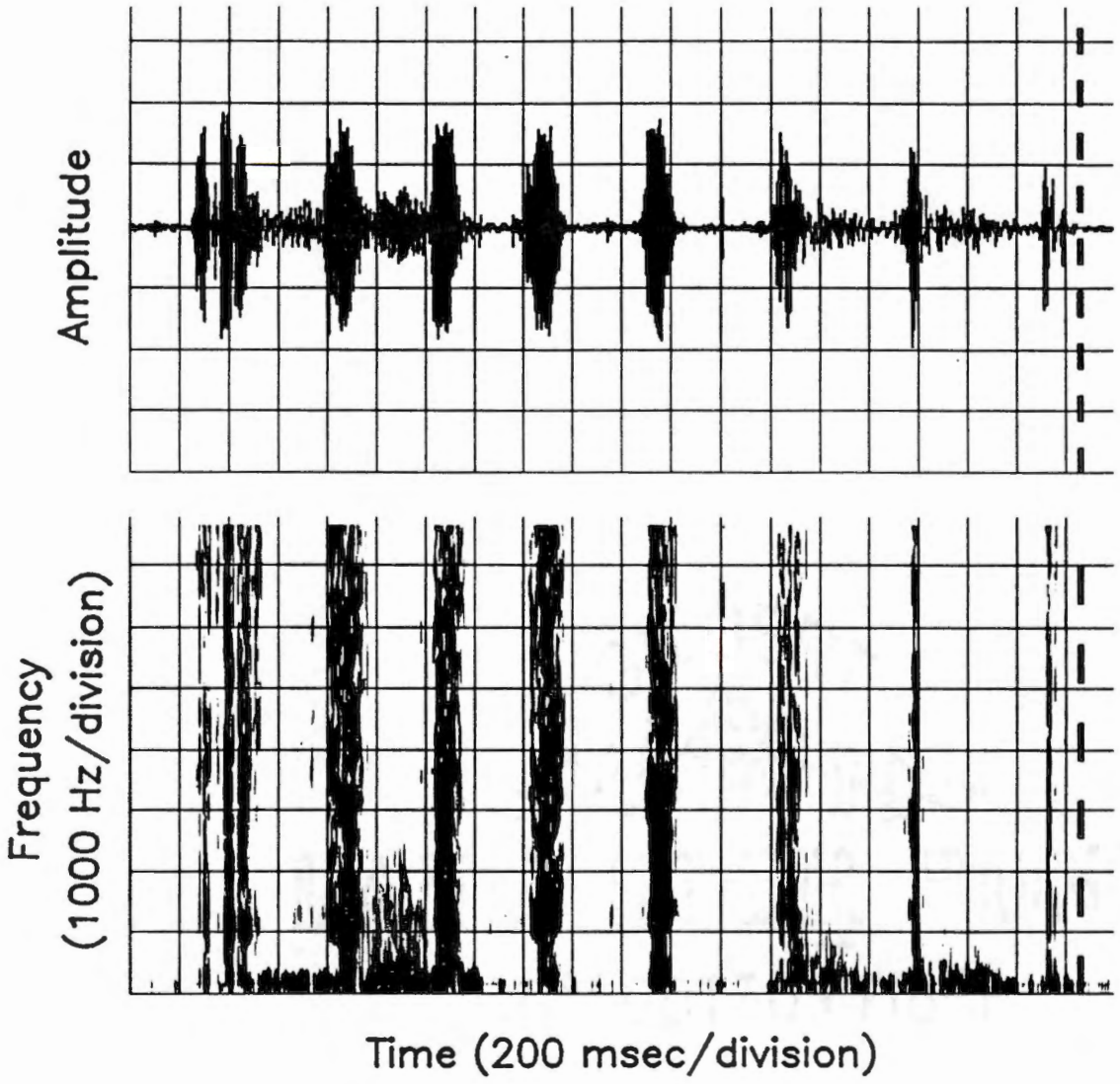


Figure III.14 – Waveform (top) and corresponding wideband spectrogram (bottom) of the sounds for the initial 8 chews of melba toast by subject 3 (adult female). Time proceeds from 0 to 4 sec from left to right. Frequency increases from 0 to 8000 Hz from bottom to top of the spectrogram. Darkness of the spectrogram indicates amplitude with amplitude increasing as darkness increases.

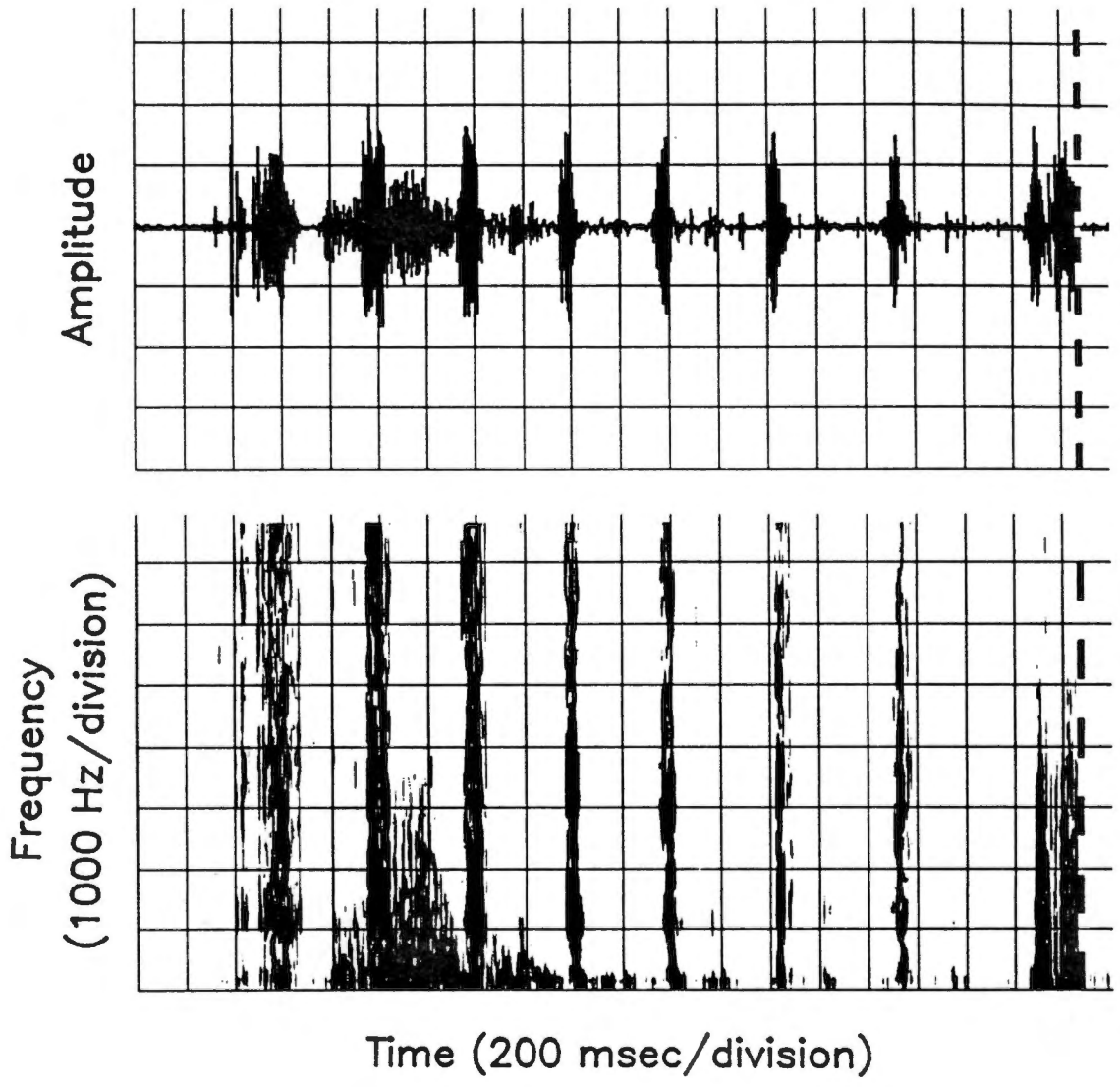


Figure III.15 – Waveform (top) and corresponding wideband spectrogram (bottom) of the sounds for the initial 8 chews of a ginger snap by subject 3 (adult female). Time proceeds from 0 to 4 sec from left to right. Frequency increases from 0 to 8000 Hz from bottom to top of the spectrogram. Darkness of the spectrogram indicates amplitude with amplitude increasing as darkness increases.

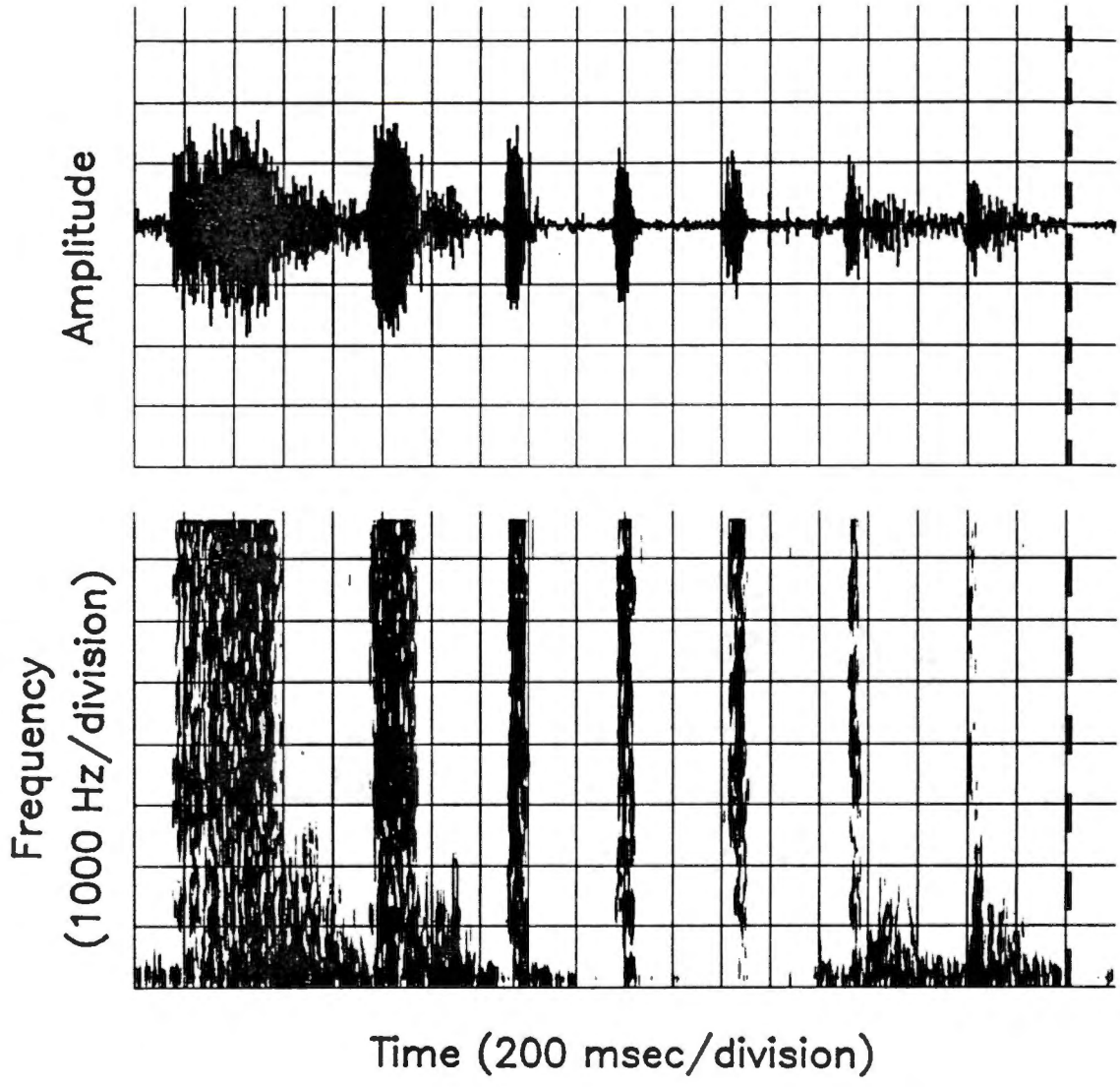


Figure III.16– Waveform (top) and corresponding wideband spectrogram (bottom) of the sounds for the initial 7 chews of a corn snack by subject 3 (adult female). Time proceeds from 0 to 4 sec from left to right. Frequency increases from 0 to 8000 Hz from bottom to top of the spectrogram. Darkness of the spectrogram indicates amplitude with amplitude increasing as darkness increases.

Durations of sounds produced by subject 2 were similar to those of sounds produced by subject 1. Waveforms and spectrograms of sounds for chews of melba toast (Figures III.2 and III.11) and ginger snap (Figures III.3 and III.12) indicate similarities in the durations of sounds for these subjects. However, differences were found between the subjects for duration of sounds for the celery. Whereas a long duration characterized sounds for successive chews of the celery by subject 1 (Figure III.8), duration of the sounds decreased with successive chews of this food sample by subject 2 (Figure III.13).

Durations of sounds produced by subject 3 were shorter than those of sounds produced by subjects 1 and 2. This difference is seen in the number of initial chews shown for the 4-sec interval of the waveforms and wideband spectrograms. For example, waveforms and spectrograms of sounds for subject 3 show the initial 8 chews for the melba toast (Figure III.14) and ginger snap (Figure III.15). In contrast, sounds for the initial 3-5 chews for these food samples are shown in the waveforms and spectrograms for subject 1 (Figures III.2 and III.3) and subject 2 (Figures III.11 and III.12). Differences in the number of chews occurring for the 4-sec interval reflects differences in the chewing rates of the subjects. Subject 3 chewed food samples at a faster rate than did subjects 1 and 2. Chewing rates of the subjects were not controlled in this experiment.

Differences in the durations of the sounds among subjects indicate that chewing rate will influence time-dependent measures of mastication sounds. Therefore, variability in these measures is expected among subjects. This suggests that for studies of duration of mastication sounds either chewing rates of subjects should be controlled or subjects with similar chewing rates should be selected for study.

Amplitude of Mastication Sounds

Both waveforms and wideband spectrograms were used to evaluate the amplitude of sounds for the initial chews of the food samples.

For waveforms, height of the sound waves indicates amplitude with amplitude increasing as the height of the waves increases. For spectrograms, darkness of the spectrographic pattern indicates amplitude with amplitude increasing as darkness increases.

Examination of waveforms and wideband spectrograms of sounds produced by subject 1 indicated differences in the amplitude of the sounds for the 10 food samples. Amplitudes of the sounds for the graham cracker (Figure III.1) and peanut (Figure III.4) were lower than those of the sounds for the other food samples. In particular, the lightness of the spectrographic patterns illustrates the low amplitude of sounds for these food samples. Additionally, amplitude decreased for sounds of successive chews of the graham cracker and peanut. In comparison, a high amplitude characterized sounds for successive chews of the hard candy (Figure III.7), celery (Figure III.8), and corn snack (Figure III.10). Both the height of the sound waves and the darkness of the spectrographic patterns illustrate the high amplitude of the sounds for these food samples.

Amplitudes of sounds produced by subject 3 were similar to those of sounds produced by subject 1. Waveforms and spectrograms of sounds for chews of melba toast (Figures III.2 and III.14) and ginger snap (Figures III.3 and III.15) indicate similarities in the amplitudes of mastication sounds for these subjects. However, differences were found between the subjects for the amplitude of the sounds for the corn snack. Whereas a high amplitude characterized sounds for successive chews of the corn snack by subject 1 (Figure III.10), amplitude of the sounds decreased with successive chews of this food sample by subject 3 (Figure III.16).

Amplitudes of sounds produced by subject 2 were lower than those of sounds produced by subjects 1 and 3. Waveforms and spectrograms of sounds for chews of melba toast (Figure III.11), ginger snap (Figure III.12), and celery (Figure III.13) illustrate differences in the amplitudes of mastication sounds for this subject. In particular, the lightness of the spectrographic pattern for sounds of the ginger snap illustrates this difference. In comparison, spectrographic patterns are darker for sounds produced by subjects 1

(Figure III.3) and 3 (Figure III.15) for the ginger snap. These differences indicate that variation in acoustical measures of amplitude for mastication sounds is expected among subjects.

Distribution of Acoustic Energy

Both waveforms and wideband spectrograms were used to evaluate the distribution of acoustic energy for sounds of the initial chews of the food samples. For sounds produced by all of the subjects, spectrograms indicated that for all food samples acoustic energy occurred across the 8000-Hz range of frequencies. This range of frequencies was used for evaluation because it is used for standard wideband spectrograms of speech sounds (Perkins and Kent, 1986; Tosi, 1979).

Spectrograms of the sounds produced by subject 1 indicate that acoustic energy was present between sounds for the chews of the melba toast, ginger snap, hard candy, celery, malted milk ball, and corn snack (Figures III.2-III.3 and III.7-III.10). This energy occurred across the 8000-Hz range of frequencies. Spectrograms of sounds produced by subject 3 also indicate that acoustic energy was present between sounds for the chews of the melba toast, ginger snap, and corn snack (Figures III.14-III.16). However, this energy occurred across the initial 3000-Hz range of frequencies and represents breath sounds for the subject. Breath sounds were heard during playback of recordings of sounds produced by subject 3. Because breath sounds may interfere with spectral characteristics of mastication sounds, subjects who produce audible breath sounds during recording should be excluded from studies of mastication sounds.

Examination of waveforms and spectrograms of sounds produced by subject 1 indicated differences in the distribution of acoustic energy for sounds of the 10 food samples. Distribution of acoustic energy was described as either bursts or continuous. Bursts characterized sounds for chews of the ginger snap, peanut, almond, carrot, and hard candy (Figures III.2-III.7). All of these samples, except the ginger snap, are reference standards for the hardness

scale of the Texture Profile Method (Muñoz, 1986; Szczesniak et al., 1963). Although bursts characterized sounds for chews of the carrot, a high moisture food, acoustic energy was continuous for sounds of the celery (Figure III.8). Additionally, acoustic energy was continuous for sounds of the graham cracker (Figure III.1), melba toast (Figure III.2), malted milk ball (Figure III.9), and corn snack (Figure III.10).

Distribution of acoustic energy was similar for most of the sounds produced by the subjects. Waveforms and spectrograms of sounds for chews of the celery (Figures III.8 and III.13) and corn snack (Figures III.10 and III.16) illustrate similarities in energy distribution for sounds produced by the subjects. However, differences were found among subjects for sounds of the melba toast and ginger snap. For the melba toast, energy was continuous for sounds by subject 1 (Figure III.2) and subject 3 (Figure III.14). In comparison, bursts characterized sounds by subject 2 (Figure III.11) for this food sample. For the ginger snap, bursts characterized sounds for subjects 1 and 2 (Figures III.3 and III.12); however, energy was continuous for sounds by subject 3 (Figure III.15).

Formants of Mastication Sounds

Formants are spectrographic features of vowel sounds. Bandwidth (range of frequencies), center frequency, and amplitude are used to describe formants (Denes and Pinson, 1963; Perkins and Kent, 1986; Tosi, 1979). Formant frequencies for vowels are the resonant frequencies of the vocal tract. The vocal tract, which is a tube closed at one end and opened at the other, acts as a resonator; therefore, it has a set of natural frequencies of vibration (Denes and Pinson, 1963; Perkins and Kent, 1986). Configuration of the vocal tract determines the formant frequencies of vowels. Because the configuration of the tract changes through articulatory movements for production of different vowels, a particular vowel has a characteristic set of formant frequencies. Some of the movements which change the configuration of the vocal tract include opening of

the jaw, rounding or spreading of the lips, and position and height of the tip, back, and main body of the tongue (Perkins and Kent, 1986; Zemlin, 1988).

Wideband spectrograms for subject 1 (Figures III.1-III.10) illustrate formants for sounds of the different food samples. In general, formants were seen for the sounds of all 10 food samples. Approximately 2 or 3 formants were clearly visible for each chew of most food samples. However, formants were less prominent for chews of the peanut and hard candy (Figures III.4 and III.7) than for chews of the other food samples.

Spectrograms for subject 3 (Figures III.14-III.16) indicate that formants of sounds by this subject were similar to those of sounds by subject 1. Breath sounds interfered with some of the formants of the sounds produced by subject 3. For example, breath sounds interfered with F1 and F2 of the second and third chews of the melba toast and ginger snap (Figures III.14 and III.15). Again, this has implications for selection of subjects for studies of mastication sounds because breath sounds would interfere with measures of formants for mastication sounds.

Formants of some of the sounds for subject 2 differed from those of sounds for subjects 1 and 3. For example, formants for chews of the melba toast and ginger snap (Figures III.11 and III.12) were less prominent for subject 2 than for subjects 1 (Figures III.2 and III.3) and 3 (Figures III.14 and III.15). In general, this may be related to the lower amplitude of sounds for subject 2, because formants represent frequency regions of high amplitude within a spectrogram.

For all food samples, F1 was the most prominent formant for all chews. This formant occurred within the 1000 to 2000-Hz range of frequencies for sounds produced by subjects 1 and 3. However, a finer analysis is needed to distinguish formants of sounds for different food samples and subjects. For this analysis, a procedure referred to as sectioning can be used. Sectioning is done with a sound spectrograph and involves FFT to obtain a spectrum of the sound. A spectrum displays amplitude as a function of frequency for a given instant in time. In spectra of vowel sounds, formants appear

as peaks. Measures of amplitude, center frequency, and bandwidth are obtained from the spectra (Denes and Pinson, 1963; Zemlin, 1988). A spectrum of the vowel sound /i/ is shown in Figure II.2.

Examination of wideband spectrograms for subject 1 indicated that transitions, or shifts, occurred for some formants. For example, F1 tended to fall at the end of the first and second chews of the carrot (Figure III.6). Additionally, F1 tended to rise and fall throughout the second chew of the hard candy (Figure III.7). Transitions have implications for measures of formants, particularly measures of bandwidth and center frequency. These measures will depend on the instant in time at which a spectrum is obtained. For example, the center frequencies of F1 will be higher for the first and second chews of the carrot if spectra are obtained at the beginning of the chews than at the end of the chews.

4. CONCLUSIONS

Drake (1965b) was the first to use sound spectrography to study mastication sounds; however, the researcher was limited by type of equipment available at the time. Despite limitations, Drake suggested that the method could be developed to provide information for characteristics of mastication sounds.

In this experiment, a digital sound spectrograph generated waveforms and wideband spectrograms for sounds of initial chews of 10 food samples differing in textural properties. Seven of the samples were reference standards for the fracturability and hardness scales of the Texture Profile Method (Muñoz, 1986; Szczesniak et al., 1963). Standard procedures for wideband spectrograms of speech sounds were used. Three subjects produced the sounds which were evaluated. Acoustical characteristics of the mastication sounds were described and compared for the food samples and subjects. Characteristics included durations, amplitudes, energy distributions, and formants.

For sounds of the 10 food samples, wideband spectrograms indicated that acoustic energy occurred across the 8000-Hz range of frequencies. Bursts characterized sounds for chews of samples which

are reference standards for the hardness scale of the Texture Profile Method. These samples included the peanut, almond, carrot, and hard candy. A short duration and low amplitude characterized sounds for chews of the graham cracker and peanut. In comparison, a long duration and high amplitude characterized sounds for chews of the hard candy, celery, and corn snack.

Dark horizontal bands occurred in the spectrographic patterns of sounds for chews of the 10 food samples. These bands were referred to as formants to conform with the terminology for spectrographic features of speech sounds, particularly features of vowel sounds (Perkins and Kent, 1986; Tosi, 1979). At least 2 or 3 formants were clearly visible for each chew of the different food samples; however, formants for chews of the peanut and hard candy were less prominent than those for chews of the other food samples. For the different samples, F1 was the most prominent formant for all chews, and this formant tended to occur within the 1000 to 2000-Hz range of frequencies.

Acoustical characteristics differed for sounds produced by the 3 subjects. Sounds by subject 2 (female) were lower in amplitude than those by subjects 1 (male) and 3 (female). The lightness of the spectrograms for sounds by subject 2 illustrated this difference. Formants for sounds of chews by subject 2 were less prominent than those for sounds of chews by subjects 1 and 3. This difference may be related to the lower amplitude of the sounds by subject 2 because formants represent frequency regions of high amplitude within a spectrogram.

Subject 3 produced sounds which were shorter in duration than those produced by subjects 1 and 2. This difference was seen in the number of initial chews occurring for the 4-sec interval of the waveforms and spectrograms. Waveforms and spectrograms for sounds by subject 3 had a greater number of chews than those for sounds by subjects 1 and 2. Differences were attributed to chewing rates of the subjects. Subject 3 chewed food samples at a faster rate than subjects 1 and 2.

Researchers have suggested that analysis of mastication sounds may provide information concerning the texture of food (Edmister and Vickers, 1985; Lee et al., 1988, 1990; Vickers, 1984b; 1987; Vickers and Bourne, 1976). However, research is needed in many areas before acoustical methods can be used to evaluate food texture. Results of this experiment relate to a few of the areas.

Future studies should include acoustical measures to differentiate mastication sounds for various foods. Based on the descriptive information from this experiment, measures of durations, amplitudes, and spectral characteristics are warranted because differences in these characteristics occurred for sounds of the 10 food samples. Drake (1965b) stated that the size of food samples will influence characteristics of mastication sounds, and this effect should be investigated. In this experiment, sizes of the samples differed; however, sample sizes were those indicated for the reference standards of the Texture Profile Method (Muñoz, 1986; Szczesniak et al., 1963). Therefore, results illustrate characteristics of mastication sounds for the reference standards.

Intrasubject and intersubject variability in acoustical measures must be examined to develop acoustical methods. Information pertaining to the variation in acoustical measures is important to the design of studies of mastication sounds. Descriptive information from this experiment indicates that variation in acoustical measures can be expected among subjects.

To develop acoustical methods, research is needed to evaluate relationships of acoustical measures to instrumental texture measures for food samples. Results of this experiment suggest that hardness and fracturability may be related to acoustical characteristics of mastication sounds.

Finally, the perception of mastication sounds should be investigated because texture is a sensory attribute of food (Bourne, 1985; Szczesniak, 1975). The Texture Profile Method, the principal method for evaluating food texture, includes both instrumental and sensory tests (Brandt et al., 1963; Friedman et al., 1963; Szczesniak et al., 1963). Two areas of perception should be considered for

study. The first area is the perception of mastication sounds in relation to the acoustical characteristics of the sounds. The second area is the perception of mastication sounds for food samples in relation to the textural characteristics of the samples. Vickers and colleagues examined the perception of mastication sounds in relation to the crispness, crunchiness, and crackliness of foods (Christensen and Vickers, 1981; Edmister and Vickers, 1985; Vickers, 1981, 1984a,b, 1985, 1987; Vickers and Christensen, 1980). However, few acoustical measures were included in these studies. Concerning the issue of acoustical characteristics of sound in general, Handel (1989) stated, "Unless we can understand what there is to hear, we cannot understand perceiving. . . ."

The second experiment (Chapter IV) of the study was based on results of this experiment. In general, results were used to establish conditions and select acoustical measures for the second experiment.

CHAPTER IV

VARIATION IN ACOUSTICAL MEASURES OF MASTICATION SOUNDS

1. INTRODUCTION

Texture is a food attribute which is important to the acceptability of food; therefore, food scientists need reliable methods to study food texture (Bourne, 1978, 1985; Szczesniak, 1975). Szczesniak (1977) stated, "There is growing awareness that instrumental texture measurements should be performed under conditions simulating as closely as possible those occurring during sensory evaluation. . ."

Currently, researchers are investigating in situ methods for examining the texture of food. Electromyography (EMG), which senses electrical potentials of the masticatory muscles, has been used to study the forces needed to break down gels and gum-based confectionary products (Amemiya, 1990; Boyar and Kilcast, 1986a; Eves et al., 1990). Researchers also have used acoustical methods to study mastication sounds in relation to the texture of food (Drake, 1963, 1965a,b; Edmister and Vickers, 1985; Lee et al., 1988, 1990; Vickers, 1984b, 1987).

Bourne (1985) reported that acoustical methods are indirect tests of texture. Therefore, food scientists need information on the acoustical characteristics which differentiate mastication sounds of foods differing in textural characteristics. In particular, information pertaining to the variation in acoustical measures is needed, because it is essential information for conducting studies of mastication sounds. However, reports of variation in acoustical measures of these sounds are lacking in the food science literature.

Drake (1963) compared spectra of mastication sounds produced by 5 subjects chewing samples of crisp brown bread. For each subject, sounds for 4 chews were analyzed. The researcher reported that peaks occurred at similar frequencies within the spectra of sounds by the 5

subjects. However, Drake indicated that dispersion occurred within the frequency range of 2000-6300 Hz of the spectra.

Drake (1965a) also examined the amplitude and loudness of mastication sounds. Six subjects chewed 6 different food samples. For each type of sample, the amplitude of sounds for 5 chews per subject was averaged. Subjects also judged the loudness of their sounds as they chewed the food samples. The researcher reported that average amplitude correlated with loudness judgments for the sounds.

Drake (1965b) used a form of sound spectrography (visible speech) to study the frequency-amplitude-time characteristics of sounds produced by 6 subjects for 9 different foods. Four repetitions per subject were obtained, and 3 chews per repetition were analyzed. Although the researcher reported significant differences in acoustical characteristics of sounds for the 9 foods and for the 6 subjects, Drake emphasized that differences in the sizes of the food samples probably influenced the results of the study.

Cardello and Segars (1989) recently reported on the need for keeping sizes of food samples uniform in studies of food texture. The researchers examined the effect of 3 sizes of food samples on sensory evaluation scores of hardness and chewiness and found that these scores increased as the size of the samples increased. However, these differences became smaller as panelists were given a greater number of cues concerning size differences.

Vickers and colleagues studied noise bursts (sound occurrences) of mastication sounds for crisp and crackly foods (Edmister and Vickers, 1985; Vickers, 1984b, 1987). In these studies, sounds for the first bite with the incisors and subsequent chews with the molars were analyzed. Analysis was limited to sounds produced by one of the investigators. Vickers (1984b) reported that the number of noise bursts of sounds for the bite and first subsequent chew correlated with sensory evaluation scores of crackliness for 11 food samples. Edmister and Vickers (1985) reported that for 48 food samples the logarithm of the number of noise bursts times the mean amplitude of the bursts for the bite and 2 subsequent chews correlated with

auditory crispness of the food samples. Auditory crispness was based on crispness scores assigned to the food samples by subjects who listened to recordings of mastication sounds for the samples.

Recently, Vickers (1987) studied the noise bursts of sounds for 5 brands of potato chips. In this study, sounds produced by 4 subjects were analyzed, and analysis was limited to sounds for the first bite of the chips. Force-deformation measures also were obtained for the chips. Vickers reported that a combination of the number of noise bursts, mean amplitude of the bursts, and either peak force or slope of force-deformation curves correlated with sensory evaluation scores of crispness for the potato chips.

Lee et al. (1988) examined the spectra of mastication sounds for 7 of 10 consecutive chews of fresh and stale samples of potato chips and tortilla chips. Sounds were analyzed for 10 subjects who chewed food samples with their mouths closed. To control the chewing rates of the subjects, a flashing light metronome was used as a cue for the subjects to chew. For each type of food sample, 2 sound samples per subject were analyzed. For the 10 subjects, spectral information was averaged for each of the 7 chews to produce a single spectrum for each chew of the different food samples. The researchers reported that spectral peaks occurred in the range of 3000-4000 Hz and at 6000 Hz in the spectra for the first chew of the potato chips and tortilla chips. Amplitude of the peaks were greater for sounds of the stale chips than for sounds of the fresh chips. The researchers suggested that the initial phase of mastication may provide more information than the later phases particularly in the assessment of crispness.

Lee et al. (1990) used a sound level meter to measure the "total sound intensity" of sounds for 15 consecutive chews of fresh and stale samples of potato chips and tortilla chips. Ten subjects chewed the food samples at the rate of 1 chew/sec. Both the open-mouth and closed-mouth chewing procedures were examined. For each type of food sample and chewing procedure, 2 sound samples per subject were analyzed. For the 10 subjects, intensity measures were averaged for each of the 15 chews producing an average intensity measure for a chew. The researchers reported that intensity of the

sounds decreased with each chew; however, sounds for the fresh chips were not significantly different from sounds for the stale chips. In contrast, the open-mouth chewing procedure produced sounds higher in intensity than those produced by the closed-mouth procedure for the initial 4-5 chews.

Review of the studies of mastication sounds indicates that information is lacking for variation in acoustical measures of these sounds. Lee et al. (1988, 1990) stated that variation in acoustical measures is expected because of the nature of the sources. In addition to variation within the food samples, the researchers mentioned the following sources which pertain to physiological characteristics of subjects: structure of the oral cavity; rate of salivation; manner of force application during mastication; and magnitude of force applied during mastication.

Boyar and Kilcast (1986b) and Heath and Lucas (1987) emphasized the need for assessing the oral status of subjects participating in studies of mastication, because oral status influences chewing cycle patterns. In addition to evaluating dentition and occlusion, the researchers recommended assessment for oro-facial pain.

Another area of concern is measurement of the acoustical characteristics of mastication sounds. Measurements should be based on principles of acoustics. Because information in the food science literature is limited for mastication sounds, a model would aid in conducting studies of these sounds. This model should serve as a frame of reference for the selection and measurement of acoustical characteristics.

Mastication sounds are similar to speech sounds in that they are produced within the oral cavity which is part of the vocal tract used for production of speech sounds. Speech scientists have developed numerous acoustical methods for analysis of speech sounds. Speech scientists also are aware of factors which influence the acoustical characteristics of speech sounds. For example, resonance of the oral cavity affects the spectral characteristics of speech sounds (Denes and Pinson, 1963; Perkins and Kent, 1986). Variation in acoustical measures of speech has been related to factors such as learned

speaking differences and anatomical, physiological, and psychological conditions at the time of utterance (Tosi, 1979; Zemlin, 1988).

In this experiment, speech analysis techniques were used to study mastication sounds for cylindrical food samples differing in diameter and textural properties. Primarily, the objective of the experiment was to study intrasubject and intersubject variation in acoustical measures of sounds for the initial 2 chews of the food samples. Based on the results of these studies of variability, the following also were examined: effect of sample diameter on acoustical measures of the sounds; effect of type of food on acoustical measures of the sounds; and the relationship of acoustical measures to instrumental measures of hardness and fracturability for the food samples. Additionally, speech sounds were examined for the subjects because speech was the model for this experiment.

2. MATERIALS AND METHODS

Food Samples

Two different foods were used to prepare the test samples in the experiment. Foods included raw carrot (Wm. Bolthouse Farms, Inc., Grant, MI) and Zwieback Teething Toast (Nabisco Brands, Inc., East Hanover, NJ). These foods were selected for study because of differences in physical structure and the ability to control sample dimensions.

Sample preparation

Sixteen pounds of carrots were purchased on the same day from a local grocer and used throughout the experiment. Carrots were stored in plastic bags at 4°C during this time (7 da). One lot of Zwieback Teething Toast also was purchased from a local grocer and used throughout the experiment.

Carrots and slices of teething toast were cored to form cylindrical samples. Three different sizes (diameters) of samples were prepared for each type of food. Steel meat corers (G.R.

Manufacturing Co., Manhattan, KS) were used to prepare cylindrical samples of the following sizes: 1.27 x 1.27 cm, 1.27 x 1.90 cm, and 1.27 x 2.54 cm. Teething toast samples were cut, placed in sealed plastic bags, and stored in air-tight plastic containers at 20°C for approximately 1 wk prior to testing. Carrot samples were cut, placed in an air-tight plastic container with 200 mL of distilled water, and stored at 4°C for approximately 16 h prior to testing. For testing, subjects received 10 of each type (size, food) of sample. Three carrots were used to prepare all of the carrot samples for one subject.

Moisture content

As an indicator of quality of the food samples, moisture content of the samples was evaluated according to AOAC method 7.0003 (AOAC, 1984). Means were based on 3 determinations. For evaluation, samples were prepared in the manner previously described for preparation of samples for each subject. Because the size of the center core of the carrot samples depended on the size of the carrot used to prepare the samples, moisture content was evaluated for each size of carrot sample to determine if this had an effect on moisture content. In contrast, sample sizes were combined for evaluation of teething toast samples. To monitor the moisture content of the carrot and teething toast samples during the period in which the mastication sounds were recorded, moisture content was evaluated preceding and following the recording period.

Instrumental texture measures

The Instron Universal Testing Machine (model 1132, Instron Corp., Canton, MA) was used to evaluate textural characteristics of the food samples. Testing conditions were as follows: 500-Kg load cell, 5.5-cm flat compression anvil, 50 mm/min crosshead speed, and 200 mm/min chart speed. For the 1.27- x 1.90-cm and the 1.27- x 2.54-cm carrot samples, a range of 10 was used. A range of 5 was used for all other samples.

Samples were compressed once to produce "one-bite" force-distance curves from which measures of hardness and fracturability were obtained. Preliminary work revealed that a second compression of all samples produced curves which were too small to obtain accurate measures of other types of textural characteristics. From the "one-bite" curves, measures of hardness and fracturability were determined in the manner described by Bourne (1978, 1985). Hardness was the force (Kg) at maximum compression (80%) of the samples. Fracturability was the force (Kg) at the first significant break in the curve.

Because curves for the samples of teething toast had multiple peaks, measures of peak force also were obtained. These measures were the force (Kg) for the highest peak in the curve and the distance (cm) of that peak from the initial point at which the curve left the baseline of the strip chart. For carrot samples, measures of peak force were the same as those for fracturability. For the teething toast samples, however, the highest peak occurred after the peak for fracturability.

Generalized force-distance curves for "one-bite" compressions of carrot and teething toast samples are shown in Figure IV.1. Measures of textural characteristics from these curves are illustrated in the figure. For evaluation, samples were prepared in the manner previously described for preparation of samples for the subjects. Twenty samples were tested for each type of food sample (1 food, 1 size) on the same day.

Subjects

Six adult subjects (3 females and 3 males) produced the mastication sounds and speech sounds which were analyzed in the experiment. Subjects, ranging in ages from 19-33 yrs, were students in the College of Agriculture at The University of Tennessee, Knoxville. These subjects were selected from 10 adult volunteers (6 females and 4 males) screened for the experiment. Selection was based on results of tests of masticatory performance and oral status

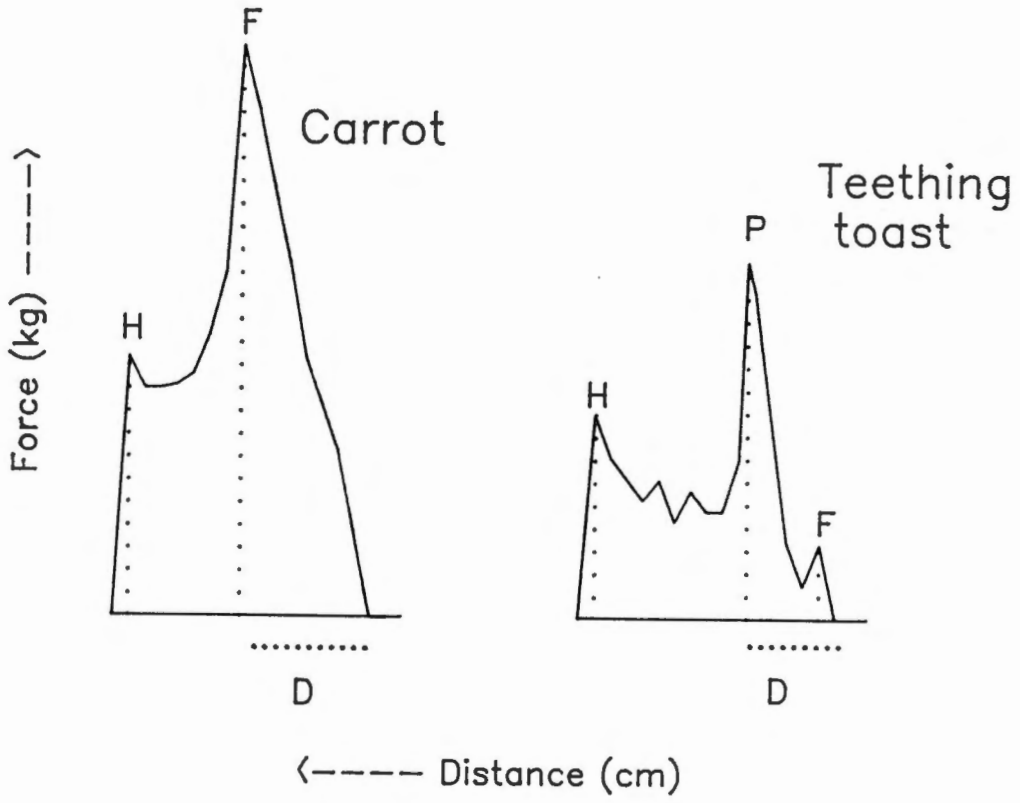


Figure IV.1 – Generalized force-distance curves from an Instron Universal Testing Machine for "one-bite" compressions of carrot and Zwieback Teething Toast samples: D=distance (cm), F=fracturability (Kg), H=hardness (Kg), and P=peak force (Kg). For carrot sample F=P.

of the subjects because these factors influence chewing cycle patterns (Boyar and Kilcast, 1986b; Heath and Lucas, 1987).

Oral status

The temporomandibular joints (TMJs) and occlusions of the 10 volunteers were examined by Gibbs M. Prevost, D.D.S (1990). Occlusions were examined in the protrusional and lateral excursions for altered mandibular movements which would affect the chewing cycle pattern. The TMJs were examined by palpation for dysfunctions which would limit mandibular movements or cause "popping" and "clicking" sounds from the joints during mastication (Lerman, 1973; Nishioka and Montgomery, 1988; Prevost, 1990). Results of the examinations indicated that all of the volunteers had normal occlusions and TMJs (Prevost, 1990).

Masticatory performance

Two types of tests were conducted to evaluate the masticatory performance of the 10 volunteers. These included a test of chew count and a test of chewing and compression rates. Other researchers have used these tests to evaluate masticatory performance (Bourne, 1977, 1985; Harrington and Pearson, 1962). The 2 tests were conducted in the same session. Half of the 10 volunteers did the test for chew count first, and the other half did the test for chewing and compression rates first. The tests were repeated in a second session held on a different day to include in the evaluation day-to-day variability. The order for testing was reversed for the second session.

Chew counts were the mean number of chews that the individuals needed to prepare a gum drop (Brach's Spicettes, Jacobs Suchard, Inc., Chicago, IL) to the state for swallowing. A gum drop was used for the test, because it is the standard food for training panelists to control their chewing rates for the Texture Profile Method (Szczesniak, 1975). During each testing session, 5 repetitions per individual were obtained.

The procedure described by Bourne (1985) was used to determine chewing rate (chews/min) and compression rate (cm/min). During each testing session, 3 repetitions for each individual were obtained with the procedure. The individuals masticated a stick of chewing gum (Wrigley's Spearmint, Wm. Wrigley Jr. Co., Chicago, IL) to a "steady state" (consistent mass) and then counted the number of chews per min. The distance (cm) between the right lateral incisors at the point of maximum opening of the mouth in the chewing cycle also was measured. The equation reported by Bourne (1985) and indicated in Appendix A was used to calculate compression rates for the subjects.

Chew counts, chewing rates, and compression rates for the 10 volunteers are shown in Table IV.1. Chew counts ranged from 13-41 chews, indicating that the individuals varied in the number of chews needed to prepare a gum drop to the state for swallowing. However, the range (18-22 chews) was narrower for volunteers 1, 4, 5, 6, and 8 than for all 10 volunteers. Chewing rates ranged from 43-106 chews/min for the 10 volunteers. In comparison, a range of 66-87 chews/min for volunteers 1, 2, 3, 7, 8, and 9 suggested that these individuals chewed gum at similar rates. Compression rates also varied for the 10 volunteers. Rates ranged from 37-206 cm/min; however, the range (74-94 cm/min) was narrower for volunteers 1, 5, 8, and 10 than for all 10 volunteers.

Selection

Three males and 3 females were selected for the experiment from the 10 volunteers. An equal number of males and females was selected to evaluate the acoustical measures in relation to gender of the subjects. Acoustical characteristics of speech sounds, the model for this study, has been related to gender of the speaker. Peterson and Barney (1952) reported that the fundamental frequencies (F_0s) and formant frequencies for 10 different vowels were lower for adult males than for adult females.

Because all 10 volunteers had normal occlusions and TMJs, selection of the 6 subjects was based on tests of masticatory performance. Primarily, chewing rates were used for selection

Table IV.1 – Mean chew counts, chewing rates, and compression rates for the 10 volunteers[a]

Subject	Chew count[b]	Chewing rate[c] (chews/min)	Compression rate[c] (cm/min)
Female			
1	21 ± 2	69 ± 2	74 ± 15
2	13 ± 2	69 ± 2	206 ± 16
3	41 ± 4	77 ± 6	197 ± 21
4	18 ± 4	43 ± 2	37 ± 4
5	22 ± 2	45 ± 2	94 ± 15
6	20 ± 2	94 ± 4	165 ± 43
Male			
7	25 ± 4	70 ± 3	156 ± 18
8	20 ± 2	87 ± 7	93 ± 29
9	16 ± 2	66 ± 2	191 ± 32
10	32 ± 3	106 ± 14	80 ± 16

[a]Means ± standard deviations.

[b]Means based on the number of chews needed to prepare a gum drop to the state for swallowing; n=10.

[c]Means based on the number of chews/min of chewing gum masticated to a "steady state"; n=6.

because results of the first experiment (Chapter III) in this study suggested that chewing rate influences the duration of mastication sounds. Because volunteers 1, 2, 3, 7, 8, and 9 had the narrowest possible range of chewing rates (66-87 chews/min) for a combination of 3 males and 3 females, these volunteers were selected for the experiment. Throughout the remainder of this chapter, volunteers 1, 2, and 3 (females) are referred to as subjects 1, 2, and 3, respectively. Similarly, volunteers 7, 8, and 9 (males) are referred to as subjects 4, 5, and 6, respectively.

Oral-cavity volume

The size of the oral cavity was evaluated for each of the 6 subjects selected for the experiment because this may influence mastication sounds. In particular, spectral characteristics of the sounds may be affected because the oral cavity is an air-filled cavity which acts as a resonator. Resonance of an air-filled cavity depends in part on the size of the cavity (Denes and Pinson, 1963; Small, 1973; Zemlin, 1988).

To evaluate the size of the oral cavity, the amount (volume) of water that subjects were able to take into their mouths was examined. This procedure was used because a procedure for determining oral-cavity volume was not found in the food science literature. Additionally, this procedure was suggested by a dentist as a means of measuring the volume of the oral cavity (Adkins, 1990). Subjects were given 175 mL of distilled water in a white opaque plastic cup. They were instructed to fill their mouths to maximum capacity with the water and then expectorate the water into a beaker. Graduated cylinders then were used to measure the amount of water. Two drinking procedures for filling the mouth were examined. These procedures included sipping the water with a flexible plastic straw and drinking the water directly from the cup. Both procedures were done in the same testing session. Half of the subjects used the straw method first, and half used the direct sipping method first. Prior to testing, subjects practiced each procedure twice. Eight repetitions per subject were obtained for each procedure.

Mastication Sounds

Mastication sounds for the 6 subjects were recorded and then analyzed. For each subject, sounds for 6 sets of food samples were recorded. Each set consisted of 10 samples of 1 type of food sample (1 food, 1 size). For each subject this provided 10 sound samples for each type of food sample for evaluating intrasubject variability in acoustical measures. Each subject completed 1 set of food samples before going to the next set of food samples. Sets of food samples were presented individually and in random order to the subjects. All samples were room temperature (approximately 20°C), and subjects used room-temperature bottled water (Mountain Valley Water, Hot Springs, ARK) for rinsing their palates. Sounds for each subject were recorded in 1 session (approximately 1 h), and sounds for the 6 subjects were recorded over a period of 3 da.

Prior to recording, subjects were given instructions for chewing the food samples. Instructions were reinforced between sets of the food samples during the recording sessions. Subjects were instructed to place each cylindrical sample of food between the molar teeth and to orient the sample so that the flat surfaces of the cylinder were parallel to the surfaces of the molar teeth. Subjects also were instructed to chew the samples with the molar teeth. This technique was used because it is used for sensory evaluation of hardness for the Texture Profile Method (Brandt et al., 1963; Muñoz, 1986). Subjects also chewed the samples with their mouths open to maximally capture sounds for recording. Following the instructions, subjects were given two 1.27 x 2.54 cm carrot samples to practice the chewing procedure.

For recording, subjects were seated in a sound treated booth (model 140, I.D.E. Process Corp., Noise Control Division, New York, NY) to reduce the level of environmental noise. Prior to recording, a sound level meter (model 155, Quest Electronics, Oconomowoc, WI) was used to measure the level of background noise in the booth. The noise level (L_A) of the booth was 33 decibel (dB).

Shown in Figure IV.2 is a block diagram illustrating the system for recording the mastication sounds. The system consisted of the following: 2.54-cm condenser microphone (model 4145, Bruel and Kjaer Instruments Inc., Denmark); 1.27-cm preamplifier (model 2619, Bruel and Kjaer Instruments Inc.); microphone power supply (model 2807, Bruel and Kjaer Instruments Inc.); attenuator (350C Attenuator Set, Hewlett Packard); and tape recorder (model TC-399, Sony, Japan). The Hewlett Packard attenuator was used to calibrate the intensity of the sounds captured by the tape recorder. All mastication sounds were recorded at a level of -7 to +1 dB, in reference to the VU meter of the recorder. For recording, the microphone was positioned 6 cm from the mouths of the subjects. Sounds were recorded on 0.635-cm audio-magnetic tape (3M/Scotch, St. Paul, MN) with the tape recorder operated at a speed of 19 cm/sec.

A 1000-Hz tone at a level of 80 dB also was recorded under the same conditions as those for the mastication sounds. The recorded tone was used for daily calibration of the instruments used for acoustical analysis of the mastication sounds. A 1000-Hz tone was used because it is the standard reference tone for calibrating instruments (Cudahy, 1988). A level of 80 dB was used because preliminary work revealed that mastication sounds produced by 2 adult females under these recording conditions were either at or below 80 dB when measured with a sound level meter (model 155, Quest Electronics, Oconomowoc, WI). The tone was generated by a pistonphone (model CA-22 Calibrator, Quest Electronics, Oconomowoc, WI) for 3 min and quantified with the sound level meter.

Acoustical Analyses

Acoustical analysis of the mastication sounds is described in this section. Prior to analysis, recordings of the calibration tone and mastication sounds were rerecorded electrically. For rerecording, sounds were played back from the Sony tape recorder (model TC-399) and recorded on 0.635-cm audio-magnetic tape (3M/Scotch, St. Paul, MN) with a Pioneer tape recorder (model

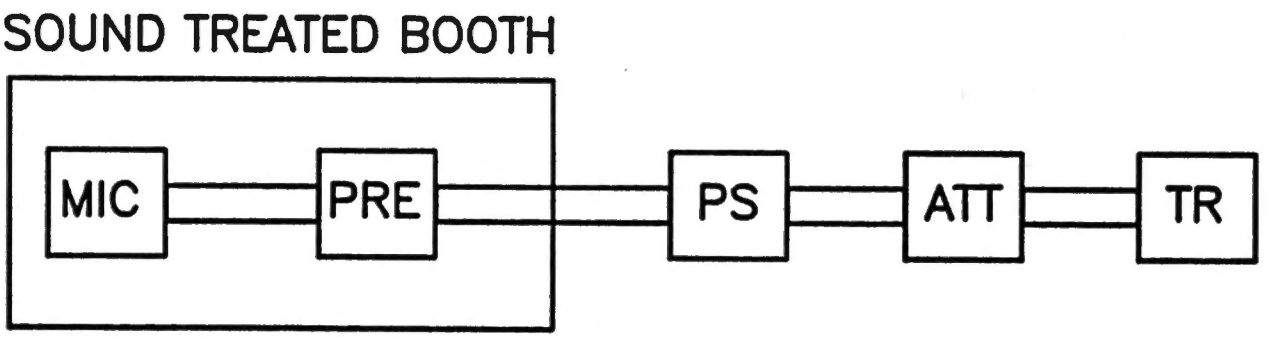


Figure IV.2 – Block diagram of system for recording mastication sounds: MIC=microphone, PRE=preamplifier, PS=power supply, ATT=attenuator, and TR=tape recorder.

Japan). Both recorders were operated at speeds of 19 cm/sec. The playback and recording levels of the recorders were held constant for recording of all sounds. For acoustical analysis, the Pioneer tape recorder was used to playback these recordings. The recorder was operated at a speed of 19 cm/sec, and the playback level of the recorder was held constant for comparison of amplitude of the mastication sounds.

Acoustical analysis was limited to sounds for the initial 2 chews of the food samples because instrumental texture measures for the Texture Profile Method are based on "two-bite" compression curves (Bourne, 1978; Szczesniak and Einstein, 1974; Szczesniak et al., 1963). The types of analysis done were based on results of the first experiment (Chapter III) of this study. Descriptive information from the first experiment indicated that acoustical characteristics varied for sounds of the initial chews of 10 food samples differing in textural properties. Differences appeared in the durations, amplitudes, energy distributions, and formants of the sounds. Therefore, these characteristics were evaluated in this experiment. For evaluation, sound spectrography (spectrographic analysis) and oscilloscopic analysis were used. Spectrographic analysis included the use of wideband spectrograms, average power spectra, and amplitude displays.

Wideband spectrograms and average power spectra

Wideband spectrograms and average power spectra were used for analysis of the durations and formants of the mastication sounds. For analysis, a digital sound spectrograph (DSP Sona-Graph, model 5500, Kay Elemetrics Corp., Pine Brook, NJ) and a gray scale printer (model 5510, Kay Elemetrics Corp., Pine Brook, NJ) were used.

Standard procedures for wideband spectrograms of speech sounds were used for analysis of the mastication sounds (Perkins and Kent, 1986; Tosi, 1979). Procedures included the use of a 100-point transform size for FFT, an 8000-Hz range of frequencies for analysis, and high frequency input shaping (high shaping). High shaping placed a 6 db/octave emphasis on frequencies greater than 1000 Hz. This

emphasis permitted evaluation of formants at these frequencies. The following measures of duration (msec) were obtained from the wideband spectrograms: duration of the first chew (chew 1); duration of the second chew (chew 2); duration of the interval between chews (between); duration from the onset of the first chew to the onset of the second chew (onset); and duration from the onset of the first chew to the end of the second chew (total). Although subjects having similar chewing rates were selected for this experiment, these measures were obtained to evaluate chewing patterns of the subjects for the 2 chews of the different food samples. Descriptive information from the first experiment (Chapter III) of this study indicated that the duration of mastication sounds differed for subjects, foods, and for sequential chews of a food.

Average power spectra were used in conjunction with the wideband spectrograms for measurement of the center frequencies (Hz) and relative amplitudes (-dB) of formants of the mastication sounds. Whereas formants appeared as dark horizontal bands in wideband spectrograms, they appeared as peaks in the average power spectra. For the average power spectra, a 100-point transforms size for FFT and an 8000-Hz range of frequencies for analysis were used. Additionally, flat input shaping was used for measurement of formant amplitudes. Average power spectra were obtained for the initial 100 msec of the sounds for each chew, because the duration of the mastication sounds for each of the initial chews differed for the subjects and food samples. Preliminary work indicated that the durations of all sounds were at least 100 msec for all subjects and food samples. For measurement of relative amplitudes of the formants, all sounds were referenced to the recorded calibration tone which had an amplitude of 80 dB.

Amplitude display

For analysis of amplitude of the mastication sounds, the amplitude display of the digital sound spectrograph was used. In general, the amplitude display includes both the waveform and amplitude envelope of a sound. The amplitude envelope is a logarithmic envelope of the waveform. The spectrograph produces the envelope by processing the waveform. For production of the envelope, power is averaged at intervals and plotted logarithmically in decibels (dB) from the full scale output of the spectrograph. An example of this type of analysis is shown in Figure IV.3 for the sound of the first chew of a raw carrot sample (2.54 cm in diameter) by a subject 2, an adult female. In the figure, the x-axis indicates time and the y-axis indicates relative amplitude. The waveform is the upper plot and, the lower plot is the corresponding amplitude envelope. Measures of time and relative amplitude are obtained from the envelope.

For analysis of the mastication sounds, a 25-msec averaging interval was used to produce the amplitude envelope for the sounds of each of the 2 chews of the food samples. This averaging interval permitted analysis of the sounds produced by all subjects and produced a range of relative amplitude from -47 to 0 dB. Sounds for the 2 chews of the food samples were analyzed separately. From the envelope of the sound for a chew, the following measures were obtained: duration (msec); peak amplitude (-dB); and average amplitude (-dB). Peak amplitude was the amplitude at the highest point on the envelope for a chew. For measures of average amplitude, measures of amplitude were taken at 50-msec intervals throughout the envelope for a chew. These measures were summed, and the sum then was divided by the number of 50-msec intervals for the chew to produce an average measure of amplitude. A 50-msec interval was used for measurement because preliminary work revealed that average amplitude measures based on 50-msec intervals were similar to those based on 25-msec intervals, the smallest interval possible for analysis of sounds produced by all 6 subjects. Average amplitude was determined to provide estimates of the overall amplitude of the sound

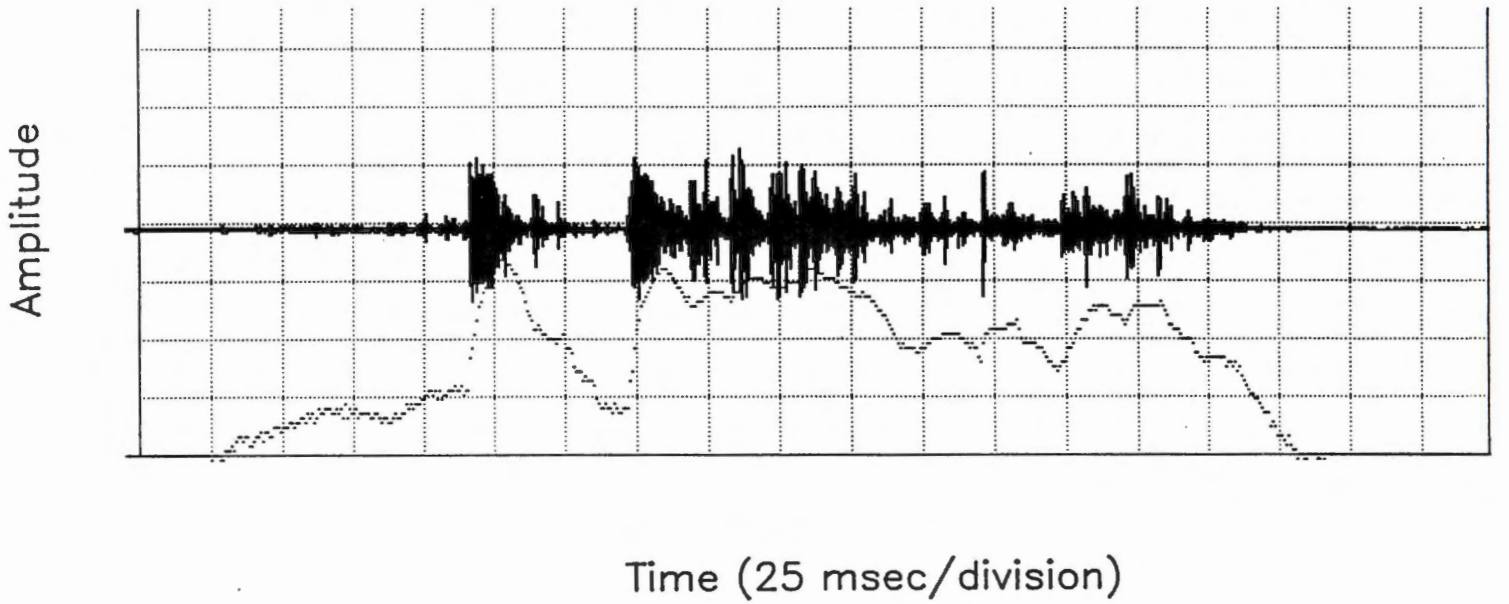


Figure IV.3 – Waveform (upper plot) and amplitude envelope (lower plot) of an amplitude display for the sound of the initial chew by subject 2 (adult female) for a raw carrot sample, 2.54 cm in diameter. The x-axis indicates time and the y-axis indicates amplitude. Time proceeds from 0 to 500 msec from left to right of the display. Amplitude increases from bottom to top of the display.

for a chew. Results of the first experiment (Chapter III) in this study indicated that the distribution of acoustic energy for a chew differed for different foods. Whereas acoustic energy was continuously distributed throughout the chews for some foods, such as celery and corn snack, bursts appeared in waveforms for the sounds of other foods, such as carrot and almond.

Oscilloscopic analysis

An oscilloscope, an instrument commonly used to evaluate the duration and amplitude of speech sound waves, has been used in previous studies of mastication sounds (Cudahy, 1988; Edmister and Vickers, 1985; Vickers, 1984b, 1987). Therefore, an oscilloscope was used to analyze the mastication sounds in this experiment. For analysis, a digital storage oscilloscope (model 206, Nicolet Instruments Corp., Madison, WI) was used. This instrument displayed waveforms of the mastication sounds on a cathode-ray tube for measurements. Waveforms for sounds of the 2 initial chews of the food samples were analyzed separately because conditions could not be established for simultaneous display of both waveforms.

The following measurements were obtained from waveforms of sounds for the initial 2 chews of the food samples: duration (msec) of the chew, peak amplitude (mv) of the chew, and time (msec) from onset of the chew to peak amplitude of the chew. Peak amplitudes were converted from mv to relative peak amplitudes (-dB) by referencing the mastication sounds to the calibration tone. First, the calibration tone was analyzed, and the peak amplitude of the tone was measured in mv. The formula reported by Flecther (1953) and indicated in Appendix A then was used to convert peak amplitude from mv to the decible (dB) scale.

Reliability

Average coefficients of variation (CVs) were used to evaluate reliability of the acoustical measures of the mastication sounds (Sokal and Rohlf, 1969; Steel and Torrie, 1960). For evaluation, 3 sound samples were randomly selected and reanalyzed. The Proc MEANS

procedure was used to compute the CVs (SAS Institute, Inc., 1985) over 3 repetitions per sound sample.

Average CVs for all acoustical measures of the mastication sounds are presented in Table IV.2. A CV of 5% was used to determine reliability because a probability level of 0.05 was used to determine significance for statistical analysis of the data in the experiment.

Averages indicate that spectrographic measures were reliable. These measures include amplitude display parameters, duration parameters, and formant frequencies and amplitudes. For both the first and second chews, averages were less than 5% and ranged from 0-3.67%. The highest averages were those for amplitudes of the first and fifth formants. However, when these averages are multiplied times the mean amplitudes of the formants, the reliability is approximately $\pm$ 1 dB. The spectrograph, in general, measures amplitude in increments of 1 dB.

In contrast, average CVs for measures from oscilloscopic analysis indicate a lack of precision. For measures of both chews, averages were greater than 5% and ranged from 9.48-11.76%. Lack of precision indicates errors in measurement. Errors can be attributed to the way in which the mastication sounds were recorded and the manner in which the oscilloscope processed and displayed waveforms of the sounds on the CRT. Whereas the spectrograph is a real-time analyzer, the oscilloscope has a sweep time. Consequently, there is a delay between the time that the instrument acquires the signal and displays its waveform on the CRT. Because sounds for consecutive chews of a food sample were recorded in sequence, it was difficult to isolate a waveform for a given chew and identify its boundaries on the CRT. Therefore, this type of analysis may be inappropriate for recordings of sequential mastication sounds.

Speech Sounds

Speech sounds are complex sounds which are produced within the vocal tract (Denes and Pinson, 1963). Similarly, mastication sounds are complex sounds produced within the oral cavity that is part of

Table IV.2 – Average coefficients of variation for acoustical measures of mastication sounds

Acoustical analysis Measure	Average coefficient of variation		
	Chew		
	1	2	Composite value
	----------%----------		
Amplitude display			
Average amplitude	1.31	1.13	----
Peak amplitude	1.15	2.16	----
Duration	0.19	0.54	----
Formant (F) frequency			
F1	1.29	0.00	----
F2	0.00	1.84	----
F3	0.50	0.75	----
F4	0.38	0.81	----
F5	0.32	0.59	----
Formant (F) amplitude			
F1	0.93	2.21	----
F2	3.67	3.23	----
F3	1.39	2.08	----
F4	1.98	2.26	----
F5	1.73	3.62	----
Duration			
Chew 1	0.77	----	----
Chew 2	----	0.72	----
Onset	----	----	0.27
Between	----	----	0.23
Total	----	----	0.25
Oscilloscopic			
Peak amplitude	11.20	10.26	----
Peak time	12.21	11.76	----
Duration	9.48	9.52	----

the vocal tract. Therefore, speech sounds were analyzed for the 6 subjects in this experiment to characterize, acoustically, the subjects as speakers. All of the subjects, except subject 4, spoke native American English. Subject 4 was a native of Venezuela.

Because the objective was to characterize the subjects as speakers, cardinal vowels, including /i/, /u/, and /ɑ/, were the sounds which were analyzed. These 3 vowels represent the extreme physiological limits of the tongue for production of all vowels regardless of language (Denes and Pinson, 1963; Handel, 1989; Zemlin, 1988). The cardinal vowel concept was described in Chapter II, section 4.

The following acoustical characteristics were studied for each vowel: durations, fundamental frequencies (F_0s), and formant frequencies. Formant frequencies and F_0s relate to the acoustical properties of the vocal tract. Formant frequencies are the resonant frequencies of the vocal tract. Fundamental frequency is the average rate of vocal fold vibration for production of voiced speech sounds, such as vowels and is related to the mass and length of the vocal folds. As the mass and length of the vocal folds increase, the F_0 decreases because the rate of vibration of the vocal folds decreases (Denes and Pinson, 1963; Perkins and Kent, 1986; Zemlin, 1988). For analysis of these characteristics, subjects sustained the vowels for production.

Recording

Prior to recording the sounds, subjects were taught to produce the 3 vowels. Subjects were instructed to produce the vowels /i/ as in "beet", /u/ as in "boot", and /ɑ/ as in "father". Correct lip and tongue positions were explained and demonstrated. Subjects then practiced producing the vowels.

For all 6 subjects, sounds for the 3 vowels were recorded and then analyzed. Subjects produced the vowels in random order. For each subject, 3 repetitions for each vowel were recorded. All sounds for a subjects were recorded in 1 session, and sounds for all the subjects were recorded over a period of 3 da. Vowel sounds and

mastication sounds were recorded in separate sessions which were held on different days.

For recording the vowel sounds, procedures similar to those for recording mastication sounds were used. Subjects were seated in the sound treated booth to reduce the level of environmental noise. The recording system shown in Figure IV.2 was used to record the sounds. The Hewlett Packard attenuator was used to calibrate the intensity of the sounds captured by the tape recorder. All vowel sounds were recorded at a level of -5 to -3 dB, in reference to the VU meter of the tape recorder. For recording, the microphone was placed 6 cm from the mouths of the subjects. Sounds were recorded on 0.635-cm audio-magnetic tape (3M/Scotch, St. Paul, MN) with the tape recorder operated at a speed of 19 cm/sec.

A 1000-Hz tone at a level of 90 dB also was recorded under the same conditions as those for the vowel sounds. The recorded tone was used for daily calibration of the digital sound spectrograph used for analysis of the vowel sounds. A level of 90 dB was used because preliminary work indicated that vowel sounds produced by 2 adult females under these recording conditions were either at or below 90 dB when measured with a sound level meter (model 155, Quest Electronics, Oconomowoc, WI). The tone was generated by a pistonphone (model CA-22 Calibrator, Quest Electronics, Oconomowoc, WI) for 3 min and quantified with the sound level meter.

Prior to acoustical analysis, recordings of the vowel sounds and calibration tone were rerecorded under the same conditions as those described for rerecording of the mastication sounds. For acoustical analysis, the Pioneer tape recorder (model RT-1011L, Pioneer Electronics Corp., Japan) was used to playback these recordings. The recorder was operated at a speed of 19 cm/sec, and the playback level of the recorder was held constant for analysis of all sounds.

For acoustical analysis of the vowel sounds, a digital sound spectrograph (model 5500, Kay Elemetrics Corp., Pine Brook, NJ) and a gray scale printer (model 5510, Kay Elemetrics Corp., Pine Brook, NJ) were used. Spectrographic analysis included the use of wideband spectrograms, average power spectra, and narrowband spectrograms.

Wideband spectrograms and average power spectra

Standard procedures for wideband spectrograms of speech sounds were used for analysis of the vowels (Perkins and Kent, 1986; Tosi, 1979). Procedures included the use of a 100-point transform size for FFT, an 8000-Hz range of frequencies for analysis, and high shaping. From the wideband spectrograms, the duration (sec) of each vowel sound was measured.

Average power spectra were used in conjunction with the wideband spectrograms to measure the center frequencies (Hz) of the first 3 formants of the vowels. The frequencies of the first 3 formants of the vowels were measured because these formants are important to a listener for recognition of the vowel (Denes and Pinson, 1963; Perkins and Kent, 1986). For the average power spectra, a 100-point transform size for FFT, an 8000-Hz range of frequencies for analysis, and flat input shaping were used. Average power spectra were obtained for the initial 100 msec of the vowel because this time interval was used for spectra of the mastication sounds.

Narrowband spectrograms

Standard procedures for narrowband spectrograms of speech sounds were used for analysis of the vowels (Perkins and Kent, 1986). Procedures included the use of a 512-point transform size for FFT, an 8000-Hz range of frequencies for analysis, and high shaping.

An example of a narrowband spectrogram for the vowel /i/ was shown in Figure II.2. In this type of analysis, vocal fold vibrations for periodic sounds, such as vowels, are analyzed as harmonics which appear as dark horizontal bars on the narrowband spectrograms (Perkins and Kent, 1986; Tosi, 1979).

Narrowband spectrograms were used to measure the F_0s (Hz) for the vowels. Fundamental frequency is a measure of the average rate of vocal fold vibration for production of the vowels. For these measurements, the 10th harmonic was located, and its frequency (Hz) was measured with the spectrograph. The 10th harmonic is the 10th horizontal bar from the bottom of the spectrogram. A measure of F_0

was calculated by dividing the frequency by 10 (10th harmonic) (Perkins and Kent, 1986; Zemlin, 1988).

Statistical Analyses

The Statistical Analysis System (SAS) was used to analyze the data (SAS Institute, Inc., 1985). Because a variety of procedures was used for analysis, the statistical procedures and models along with the rationale for their use are discussed, where appropriate, in the Results and Discussion section of this chapter. A probability level of 0.05 was used to determine significance in all of the statistical analyses in this experiment.

3. RESULTS AND DISCUSSION

Speech analysis techniques were used to study the acoustical characteristics of mastication sounds for 6 subjects who chewed samples of carrots and Zwieback Teething Toast. Because mastication sounds are produced within the oral cavity, characteristics of the oral cavities of the subjects also were assessed.

Results of the analyses are presented and discussed in this section. First, characteristics of the food samples and of the oral cavities of the subjects are discussed to provide descriptions of the samples and subjects. Next, variation in acoustical measures of the mastication sounds is discussed in relation to the subjects. Finally, results are presented for the effect of sample diameter and type of food on the acoustical measures. Relationships between acoustical measures of the mastication sounds and textural characteristics of the food samples are discussed, where appropriate, throughout this section.

Characteristics of Food Samples

Foods used as samples in this experiment were selected based on the ability to control sample size and differences in their physical

properties. Therefore, moisture contents and textural characteristics of the foods were evaluated to characterize the samples.

Moisture content

Mean moisture contents of the food samples are presented in Table IV.3. Carrot samples were higher in moisture than the teething toast samples, indicating differences in the physical properties of the foods. Means also indicate that the moisture contents of all the samples were similar before and after the recording period. Additionally, moisture contents were similar for carrot samples differing in diameter.

Table IV.3 – Means ± standard deviations of moisture content of the food samples (n=3 measurements)

	Replication[a]	
Food sample	1	2
	----------%----------	
Teething toast	5.87 ± 0.01	5.89 ± 0.00
Carrot sample		
1.27-cm diameter	89.00 ± 0.29	88.55 ± 0.06
1.90-cm diameter	89.00 ± 0.07	88.49 ± 0.07
2.54-cm diameter	88.59 ± 0.03	87.97 ± 0.15

[a]Moisture content of samples was determined preceding (1) and following (2) the recording period.

Instrumental texture measures

An Instron Universal Testing Machine was used to measure the following textural characteristics of the food samples: hardness (Kg); fracturability (Kg); peak force (Kg); and distance (cm) to peak force. Proc ANOVA was used for analysis of variance of the means of the measures. A fixed-effects model was assumed, and main effects included type of food (2 levels) and diameter of the food samples (3

levels). Means were calculated over 20 repetitions for each food type/sample size combination. The food type x sample diameter interaction also was tested. Tukey's range test was used to examine the main effects when the interaction was nonsignificant.

Results of the analysis of variance (ANOVA) are shown in the ANOVA Table B.1 in Appendix B. For all measures, food type and sample diameter were significant sources of variation. However, the food type x sample diameter interaction was a significant source of variation in measures of hardness, fracturability, and peak force. This significant interaction indicates that the effects of sample diameter on these measures were inconsistent and depended on the type of food. To examine trends in the results, the interactions were plotted for each of the measures. These plots are shown in Figure IV.4.

Trends were similar for hardness and peak force. For the carrot, the magnitude of these measures increased as the diameter of the sample increased. However, the increase in magnitude was larger between the 1.90-cm samples and the 2.54-cm samples than between the 1.27-cm samples and the 1.90-cm samples. For the teething toast, the magnitude of these measures also increased as the diameter of the sample increased; however differences in magnitude across sizes were smaller for the teething toast than for the carrot. Despite differences in the appearance of the force-distance curves for samples of carrots and teething toast, measures of peak force, under the conditions of this experiment, do not seem to provide additional insight into the differences in the breakdown of the foods in the Instron. Although the magnitude of the measures of hardness and peak force differed, trends across sample sizes were similar for these measures.

For the carrot samples, fracturability also increased as the diameter of the samples increased, and this difference was larger between the 1.90-cm samples and the 2.54-cm samples than between the 1.27-cm samples and the 1.90-cm samples. However, for the teething toast fracturability measures were small and were similar for all sample diameters.

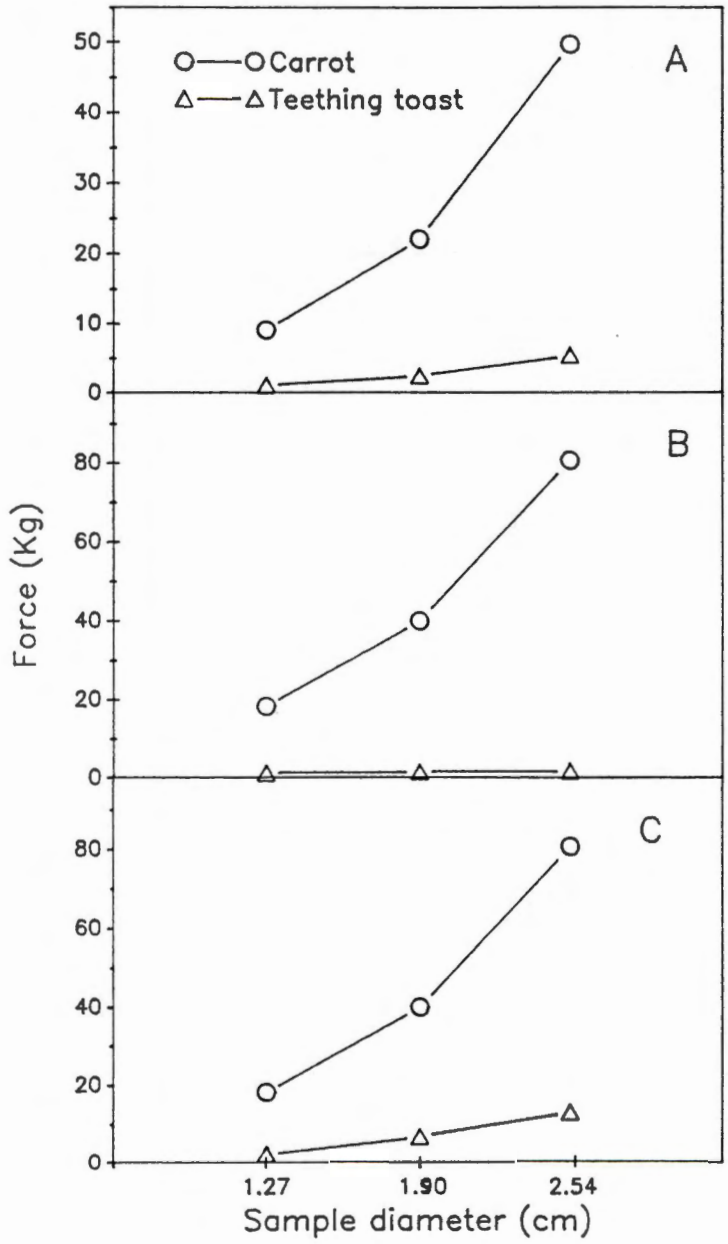


Figure IV.4 – Instron values for hardness (A), fracturability (B), and peak force (C) of raw carrot and teething toast samples as a function of sample diameter (n=20 repetitions).

For distance to peak force, both food type and sample diameter were significant sources of variation. Treatment means for distance to peak force are shown in Table IV.4. Results of the Tukey's range test revealed that distance to peak force for the carrot samples was greater than the distance to peak force for the teething toast samples. These results imply that samples of carrots were compressed a greater distance than samples of teething toast before peak force was attained. Diameter of the samples also had a significant effect distance. The 2.54-cm samples were compressed a greater distance than the 1.27 and 1.90-cm samples before peak force was attained.

Table IV.4 – Means ± standard deviations for distance to peak force (n=20 repetitions)[a]

Source Treatment	Distance (cm)
Food	
Carrot	1.5 ± 0.2x
Teething toast	0.7 ± 0.3y
Sample diameter (cm)	
1.27	1.0 ± 0.5x
1.90	1.0 ± 0.4x
2.54	1.3 ± 0.4y

[a]Means within a source followed by the same letter do not differ significantly ($p>0.05$).

Characteristics of Subjects

Characteristics of the oral cavities of the subjects were evaluated because mastication sounds are produced within the oral cavity. Characteristics included oral-cavity volume and acoustical characteristics of speech sounds.

Speech

Acoustical characteristics of the cardinal vowels /i/, /ɑ/, and /u/ were evaluated for the subjects because these vowels represent the extreme physiological limits of the tongue for production of all vowel sounds. The position of the tongue influences the characteristics of vowels because it affects the configuration of the vocal tract. The configuration of the tract determines its acoustical properties (Denes and Pinson, 1963; Handel, 1989; Zemlin, 1988).

A digital sound spectrograph was used to analyze the duration (sec), F_0 (Hz), and frequencies (Hz) of the first three formants of the vowels. Narrowband spectrograms, wideband spectrograms, and average power spectra were used for these analyses. Examples of wideband and narrowband spectrograms for the vowels are shown in Figures IV.5-IV.7. Corresponding average power spectra are shown in Figure IV.8. Examples are for sounds produced by subject 2, an adult female. Narrowband spectrograms display dark horizontal bars which are the harmonics of the vowels. Harmonics were used to determine the F_0s of the subjects for each vowel.

Proc MEANS was used to compute means and standard deviations for the acoustical measures. Means for each vowel were calculated over 3 repetitions per subject. These descriptive statistics were used to evaluate the subjects as speakers. For this evaluation, measures for the subjects were compared with those reported in the speech science literature. Primarily, results of a study of vowels by Peterson and Barney (1952) were used for comparison.

Durations of the vowels were measured to evaluate the length of time which subjects sustained the vowels for production. Mean durations are presented in Table IV.5. Means ranged from 0.70-1.99 sec and indicated that subject 4, for whom English is a second language, produced all vowels in a shorter length of time than the other subjects.

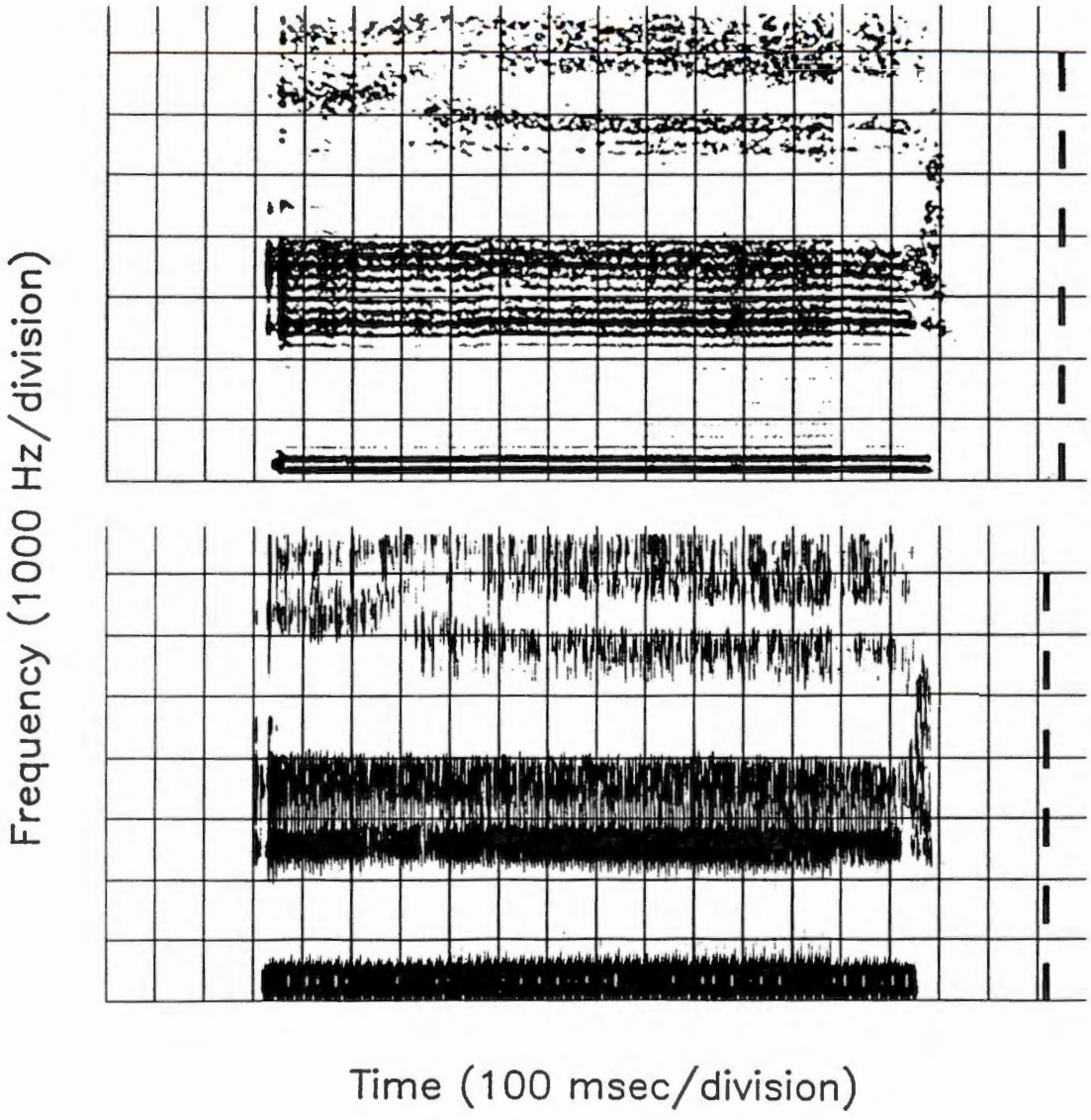


Figure IV.5 – Narrowband spectrogram (top) and corresponding wideband spectrogram (bottom) for the vowel /i/ produced by subject 2 (adult female). Time proceeds from 0 to 2 sec from left to right of the spectrograms (100 msec/vertical division). Frequency increases from 0 to 8000 Hz from bottom to top of the spectrograms (1000 Hz/horizontal division). Darkness of the spectrograms indicates amplitude with amplitude increasing as darkness increases.

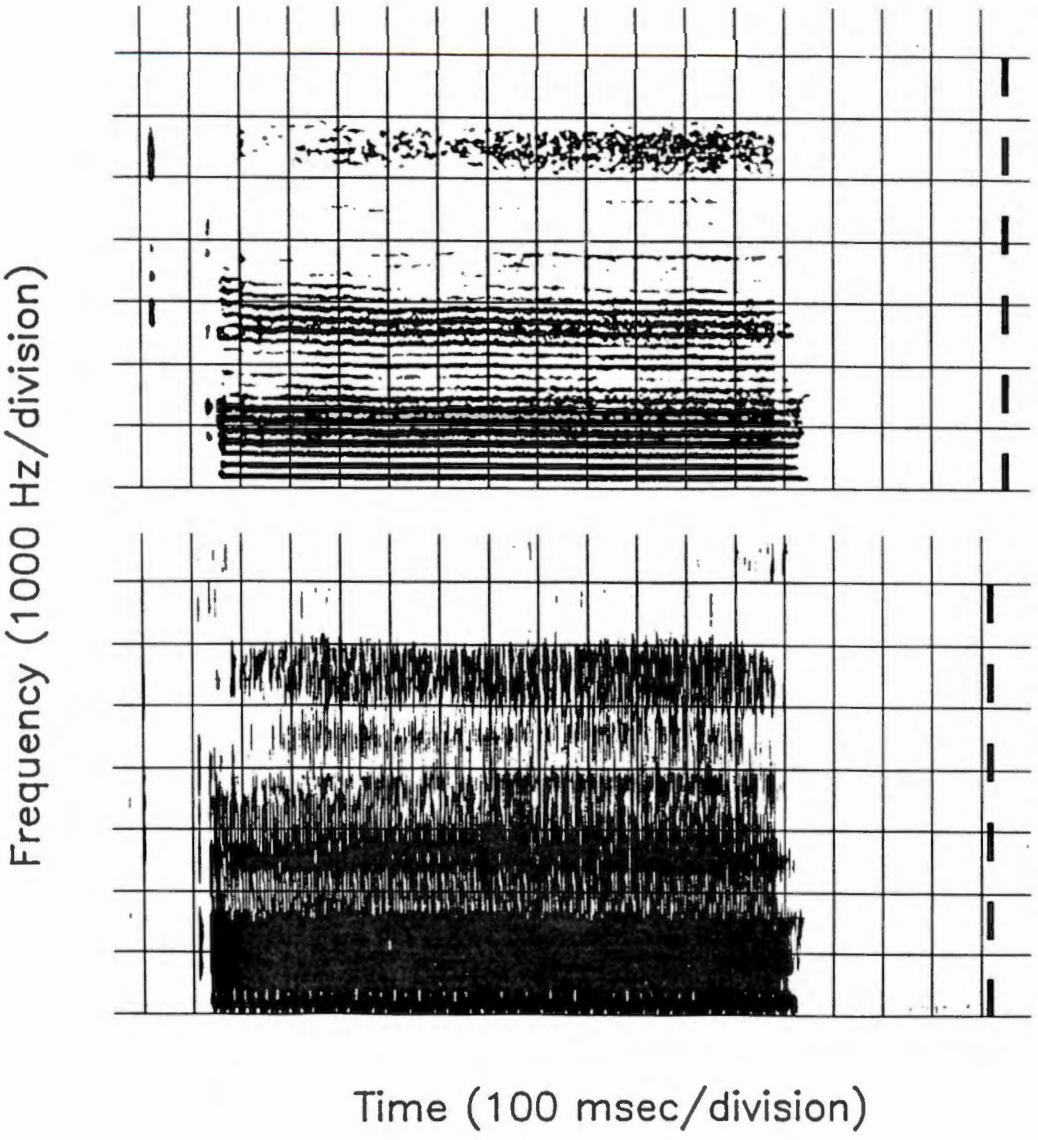


Figure IV.6 – Narrowband spectrogram (top) and corresponding wideband spectrogram (bottom) for the vowel /ɑ/ produced by subject 2 (adult female). Time proceeds from 0 to 2 sec from left to right of the spectrograms (100 msec/vertical division). Frequency increases from 0 to 8000 Hz from bottom to top of the spectrograms (1000 Hz/horizontal division). Darkness of the spectrograms indicates amplitude with amplitude increasing as darkness increases.

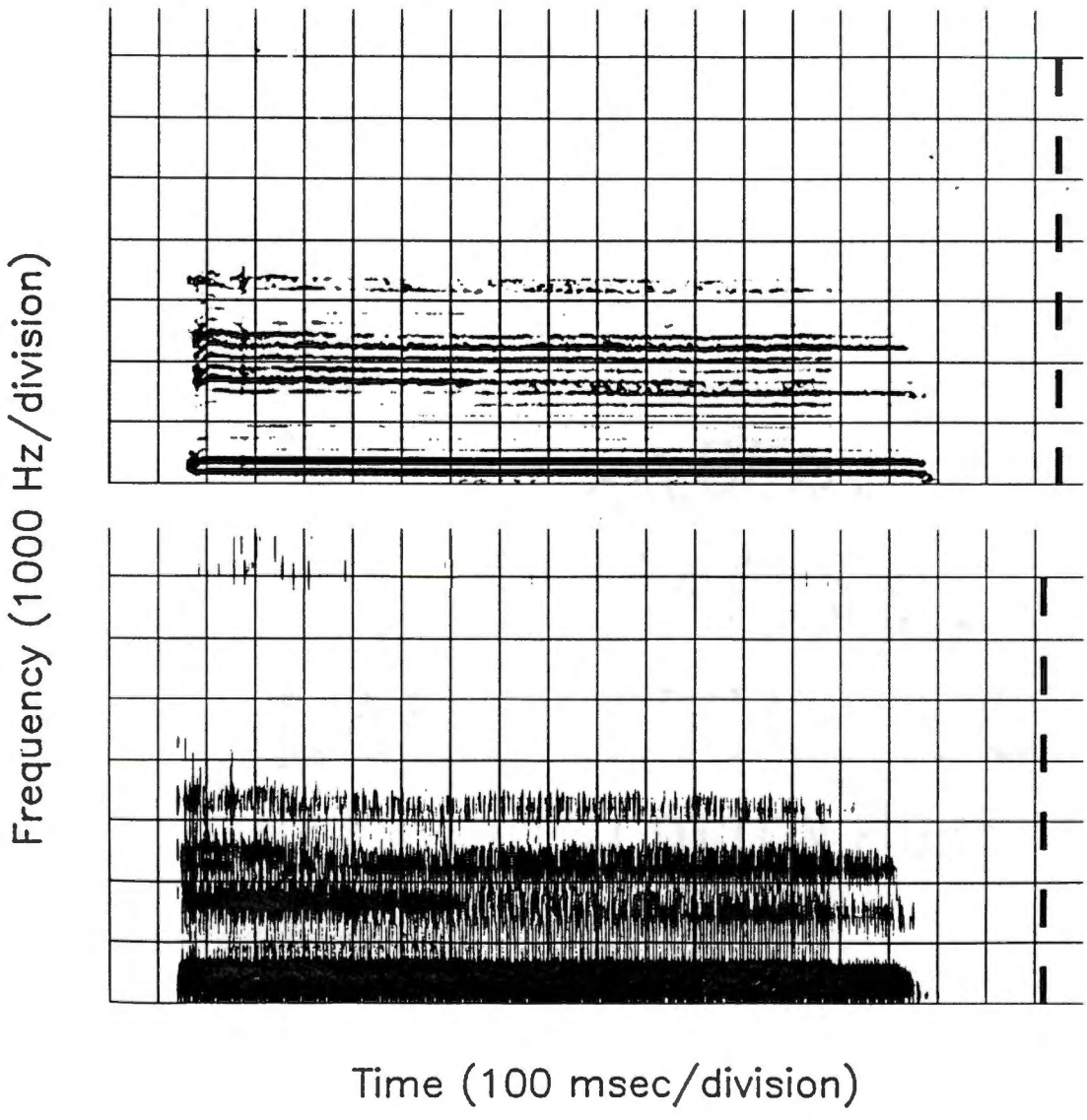


Figure IV.7 – Narrowband spectrogram (top) and corresponding wideband spectrogram (bottom) for the vowel /u/ produced by subject 2 (adult female). Time proceeds from 0 to 2 sec from left to right of the spectrograms (100 msec/vertical division). Frequency increases from 0 to 8000 Hz from bottom to top of the spectrograms (1000 Hz/horizontal division). Darkness of the spectrograms indicates amplitude with amplitude increasing as darkness increases.

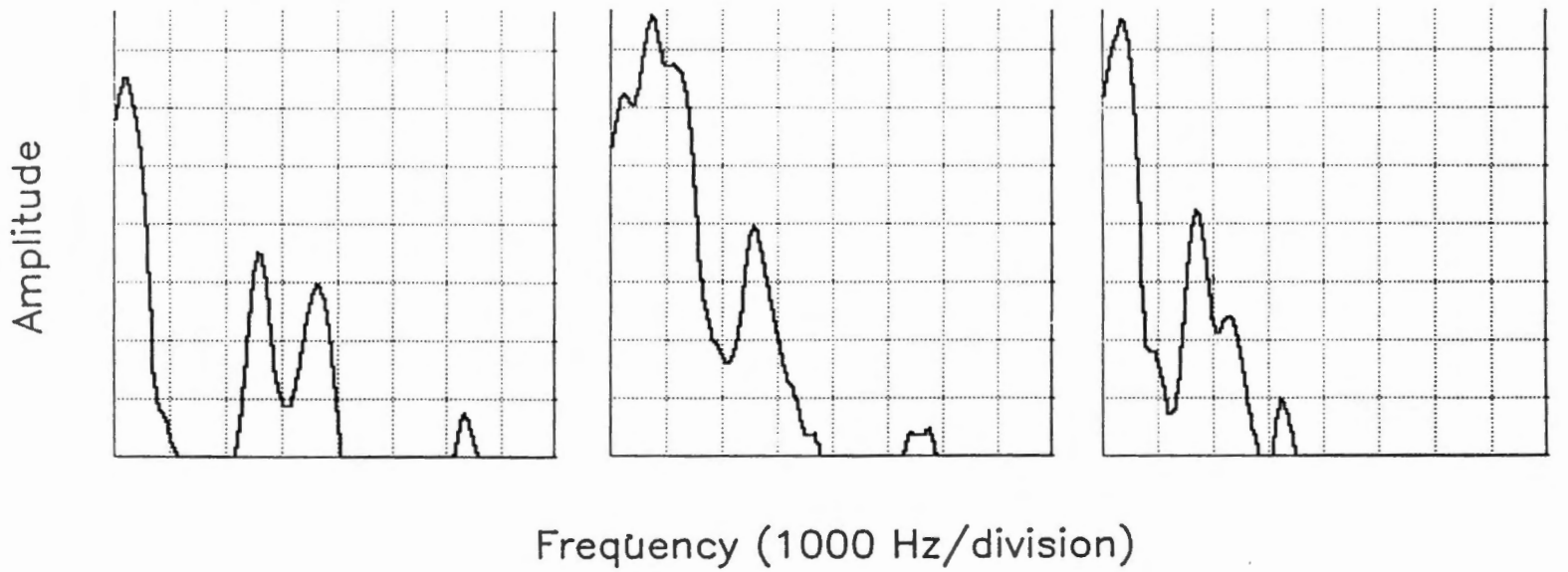


Figure IV.8 – Average power spectra for the vowels /i/ (left); /ɑ/ (center); and /u/ (right). The x-axis indicates frequency and the y-axis indicates amplitude. Frequency increases from left to right of the spectra at the rate of 1000 Hz/horizontal division. Amplitude increases from bottom to top of the spectra.

Table IV.5 – Means ± standard deviations for durations of vowels produced by the subjects (n=3 repetitions)

Subject	Vowel		
	a	i	u
	----------sec----------		
1	1.32 ± 0.31	1.35 ± 0.05	1.19 ± 0.31
2	1.35 ± 0.27	1.46 ± 0.16	1.59 ± 0.23
3	1.69 ± 0.69	0.97 ± 0.09	1.21 ± 0.17
4	0.88 ± 0.05	0.70 ± 0.05	0.83 ± 0.09
5	1.51 ± 0.19	1.88 ± 0.16	1.71 ± 0.18
6	1.14 ± 0.05	1.41 ± 0.15	1.99 ± 0.25

Fundamental frequencies of the subjects for each vowel were evaluated. Fundamental frequency is the average rate of vocal fold vibration for the production of voiced speech sounds, such as vowels. Fundamental frequency depends on the speaker and is related to the mass and length of the vocal folds. As the mass and length of the vocal folds increase, F_0 decreases because the rate of vocal fold vibration decreases. Consequently, adult males tend to have lower F_0s than adult females (Denes and Pinson, 1963; Minifie, 1973; Zemlin, 1988).

Zemlin (1988) reported average F_0s of 130 Hz for adult males and 220 Hz for adult females. Mean F_0s of the subjects for the vowels are presented in Table IV.6. Means indicated that the female subjects (subjects 1-3) had higher F_0s for all vowels than the male subjects (subjects 4-6). Means ranged from 179 to 231 Hz for the females and from 107 to 149 Hz for the males. Whereas the F_0s of vowels produced by subject 1 were higher than those of vowels produced by the other subjects, F_0s of vowels produced by subject 6 were lower than those of vowels produced by the other subjects. Means ranged from 227 to 231 Hz for subject 1 and from 107 to 115 Hz for subject 6.

Table IV.6 – Means ± standard deviations for fundamental frequencies of vowels produced by the subjects (n=3 repetitions)

Subject	Vowel		
	ɑ	i	u
	----------Hz----------		
1	231 ± 8	227 ± 2	231 ± 5
2	179 ± 2	187 ± 2	189 ± 2
3	185 ± 2	200 ± 0	205 ± 6
4	111 ± 2	143 ± 2	136 ± 0
5	121 ± 2	139 ± 2	149 ± 2
6	107 ± 6	112 ± 4	115 ± 5

Fundamental frequencies of the male and female subjects in this experiment were similar to those reported by Peterson and Barney (1952) for the vowels (Table IV.7). For the vowel /ɑ/, means ranged from 179 to 231 Hz for the females and from 107 to 121 Hz for the males. For /i/, means ranged from 187 to 227 Hz for the females and from 112 to 143 Hz for the males. Means for /u/ ranged from 189 to 231 Hz for the females and from 115 to 149 Hz for the males.

In this experiment, the frequencies of the first 3 formants (F1-F3) of the vowels were evaluated. Formant frequencies of the vowels are the resonant frequencies of the vocal tract. These frequencies depend on the configuration of the vocal tract for production of the vowels. Each vowel has a characteristic set of formant frequencies because the configuration of the tract differs for the different vowels (Denes and Pinson, 1963; Minifie, 1973; Perkins and Kent, 1986).

Primarily, the position of the tongue within the oral cavity determines the configuration of the vocal tract and, therefore, the formant frequencies of vowels. For production of the vowel sound /i/, the tongue is high and in the front of the oral cavity. The sound /ɑ/ is produced with the tongue low and in the back of the

Table IV.7 – Fundamental frequencies (F_o) and formant frequencies (F) for the vowels ɑ, i, and u[a]

Parameter Subject	Vowel		
	ɑ	i	u
	----------Hz----------		
F_o			
Males	124	136	141
Females	212	235	231
F1			
Males	730	270	300
Females	850	310	370
F2			
Males	1090	2290	870
Females	1220	2790	950
F3			
Males	2440	3010	2240
Females	2810	3310	2670

[a] From Peterson and Barney, 1952.

cavity. For /u/, the tongue is high and in the back of the cavity. Position of the lips also is important for production of vowels. Whereas the lips are spread to produce the sound /i/, the lips are rounded to produce the sounds /ɑ/, and /u/ (Denes and Pinson, 1963; Zemlin, 1988).

Mean formant frequencies of F1-F3 of the subjects for the 3 vowels are presented in Table IV.8. Perkins and Kent (1986) stated that the frequency of F1 is related to the height of the tongue in the oral cavity. As the height of the tongue decreases, the frequency of F1 increases; therefore, sounds for low vowels, such as /ɑ/, have higher F1 frequencies than sounds for high vowels, such as /i/ and /u/. These differences in F1 frequencies among the vowels were noted for the subjects in this experiment. Whereas the means for the subjects ranged from 720 to 800 Hz for /ɑ/, means for the subjects ranged from 240 to 360 Hz for /i/ and from 280 to 440 Hz for /u/.

Mean F1 frequencies for the vowels produced by the subjects in this experiment were similar to those reported by Peterson and Barney (1952) (Table IV.7), although some variability was noted. In particular, variation occurred in the F1 frequencies of the vowels /ɑ/ and /u/. For /ɑ/, Peterson and Barney reported frequencies of 850 Hz for adult females and 730 Hz for adult males. For the subjects in this experiment, subject 1 (female) had and F1 frequency of 720 Hz and subject 5 (male) had an F1 frequency of 800 Hz. For /u/, Peterson and Barney reported frequencies of 370 Hz for females and 300 Hz for males. Subject 3 (female) in this experiment had an frequency of 280 Hz for /u/.

Perkins and Kent (1986) also stated that the frequency of F2 depends on whether the tongue is in the front or back of the oral cavity. When the tongue is in the front of the cavity, the frequency is higher than when it is in the back of the cavity. Therefore, front vowels, such as /i/, have higher F2 frequencies than back vowels, such as /ɑ/ and /u/. These differences in F2 frequencies among the vowels were noted for the subjects in this experiment. Mean F2 frequencies for /i/ ranged from 2213 to 2827 Hz. In

Table IV.8 – Means ± standard deviations for frequencies of the first 3 formants of vowels produced by the subjects (n=3 repetitions)

Formant (F) Subject	Vowel		
	a	i	u
	----------Hz----------		
F1			
1	720 ± 0	360 ± 0	440 ± 0
2	800 ± 0	320 ± 0	360 ± 0
3	840 ± 40	293 ± 23	280 ± 0
4	760 ± 0	240 ± 0	280 ± 0
5	800 ± 0	293 ± 23	320 ± 0
6	760 ± 0	280 ± 0	307 ± 23
F2			
1	1267 ± 92	2693 ± 46	1653 ± 92
2	1187 ± 61	2600 ± 0	1613 ± 115
3	1253 ± 46	2827 ± 23	973 ± 46
4	1227 ± 23	2507 ± 23	840 ± 40
5	1293 ± 46	2213 ± 61	1227 ± 140
6	1320 ± 0	2253 ± 23	907 ± 46
F3			
1	3000 ± 240	3173 ± 23	2627 ± 61
2	2600 ± 80	3520 ± 120	2413 ± 61
3	2773 ± 23	3560 ± 40	---
4	2333 ± 46	---	---
5	2813 ± 23	2987 ± 61	2307 ± 23
6	2480 ± 0	2973 ± 61	---

contrast, means ranged from 1187 to 1320 Hz for /ɑ/ and from 840 to 1653 Hz for /u/.

Differences were noted in the mean F2 frequencies for the subjects in this experiment and those reported by Peterson and Barney (1952) (Table IX.7). In particular, differences occurred for /ɑ/ produced by the male subjects. Whereas Peterson and Barney reported a frequency of 1090 Hz for males, means for males in this experiment ranged from 1227 to 1320 Hz, indicating that all male subjects differed. Additionally, differences occurred for both male and female subjects for /u/. Peterson and Barney reported frequencies of 950 Hz for females and 870 Hz for males. In this experiment, means ranged from 973 to 1653 Hz for the females and 840 to 1227 Hz for the males. Means indicate that subjects 1, 2, and 5 were the subjects who differed.

Amplitudes of F1-F3 also were evaluated. Mean amplitudes of F1-F3 the subjects for the vowels are presented in Table IV.9. These amplitudes are relative to a 1000-Hz tone at a level of 90 dB. For all of the vowel sounds produced by the subjects, the amplitude of F1 was higher than those of F2 and F3, indicating that acoustic energy was concentrated at the lower frequencies within the range of 0-8000 Hz. Additionally, the amplitude of F2 was higher for /ɑ/ than for /i/ and /u/. The amplitude of F3 for /u/ was too low to be measured, under the conditions of this experiment, for 3 of the 6 subjects. This difference indicates differences among the subjects in the amplitude of the vowels.

Oral-cavity volume

The size of the oral cavities of the subjects in this experiment was evaluated because mastication sounds are produced within this cavity. The size and shape of the cavity affects the configuration of the tract and determines its acoustical properties, particularly the resonant characteristics (Denes and Pinson, 1963; Handel, 1989; Zemlin, 1988).

To characterize the size of the oral cavities of the subjects, volume of the cavity was evaluated. For evaluation, the amount (mL)

Table IV.9 – Means ± standard deviations for amplitudes[a] of the first 3 formants of vowels produced by the subjects (n=3 repetitions)

Formant (F) Subject	Vowel		
	ɑ	i	u
	----------dB----------		
F1			
1	-9 ± 1	-7 ± 1	-7 ± 2
2	0 ± 1	-4 ± 2	-1 ± 3
3	-6 ± 5	-5 ± 1	-4 ± 1
4	-3 ± 2	-4 ± 1	0 ± 1
5	0 ± 2	-8 ± 1	0 ± 2
6	-1 ± 1	-5 ± 1	-3 ± 1
F2			
1	-10 ± 1	-21 ± 4	-23 ± 2
2	-2 ± 1	-21 ± 2	-21 ± 8
3	-11 ± 3	-26 ± 1	-26 ± 4
4	-5 ± 1	-31 ± 2	-21 ± 4
5	-7 ± 5	-26 ± 2	-18 ± 1
6	-5 ± 0	-28 ± 1	-29 ± 3
F3			
1	-31 ± 2	-21 ± 2	-28 ± 2
2	-20 ± 3	-22 ± 1	-26 ± 3
3	-32 ± 1	-29 ± 3	---
4	-23 ± 3	---	---
5	-21 ± 1	-24 ± 2	-27 ± 4
6	-21 ± 0	-30 ± 3	---

[a]Amplitude relative to a calibration tone (1000 Hz, 90 dB).

of water which the subjects needed to fill their mouths was measured. Two methods for filling the mouth were examined. Methods included sipping the water from a cup with a flexible plastic straw (straw method) and drinking the water directly from a cup (direct method).

Proc ANOVA was used for analysis of variance of the means of the measures. A fixed-effects model was assumed, and main effects included subject (6 levels) and drinking method (2 levels). Mean volume for each subject was calculated over 8 repetitions per method. The subject x drinking method interaction also was tested.

Results of the analysis of variance are presented in the ANOVA Table B.2 in Appendix B. The subject and drinking method main effects were significant sources of variation; however, the subject x drinking method interaction also was significant, indicating that measures of oral-cavity volume for the subjects were inconsistent and depended on the drinking method.

Means for the subjects and methods are presented in Table IV.10. Means for the subjects ranged from 42 to 90 mL for the straw method and from 44 to 100 mL for the direct method. Means indicate that all of the subjects, except subjects 1 and 6, were able to take more water into their mouths with the direct method than with the straw method. However, this difference was greatest for subject 2 who had mean volumes of 66 mL for the straw method and 100 mL for the direct method. Whereas subjects 2, 3, and 5 had similar volumes for the straw method, subjects 4 and 6 had similar volumes for the direct method. Subjects 1 and 6 each had similar volumes for the drinking methods. For both methods, volumes for subject 1 were lower than those for all other subjects, indicating that this subject was able to take less water into the mouth than the other subjects regardless of the drinking method.

Table IV.10 – Means ± standard deviations of oral-cavity volume of the subjects (n=8 repetitions)

Subject	Drinking method	
	Straw	Direct
	---------mL--------	
1	42 ± 4	44 ± 3
2	66 ± 5	100 ± 7
3	63 ± 3	76 ± 3
4	82 ± 5	91 ± 7
5	65 ± 4	82 ± 4
6	90 ± 5	91 ± 4

Acoustical Characteristics of Mastication Sounds

In general, the objective of this experiment was to examine the effects of the diameter of food samples on the acoustical characteristics of mastication sounds for food samples differing in physical properties. Examples of wideband spectrograms and amplitude displays of mastication sounds for the food samples are shown in Figures IV.9-IV.14. Examples are of sounds produced by subject 2, an adult female. In these figures, sounds of the initial 3 chews of the food samples are shown over a time interval of 2 sec (100 msec/vertical division). Time proceeds from left to right.

Wideband spectrograms display the level of acoustic energy over time for the 8000-Hz range of frequencies used for analysis of the chews. Frequency increases at the rate of 1000 Hz/horizontal division from bottom to top of the spectrograms. Darkness of the patterns indicates amplitude with amplitude increasing as darkness increases. Formants of the sounds appear as dark horizontal bands in the patterns. Amplitude displays show the waveforms (upper plots) and amplitude envelopes (lower plots) of the mastication sounds. In these displays, the x-axis indicates time and the y-axis indicates

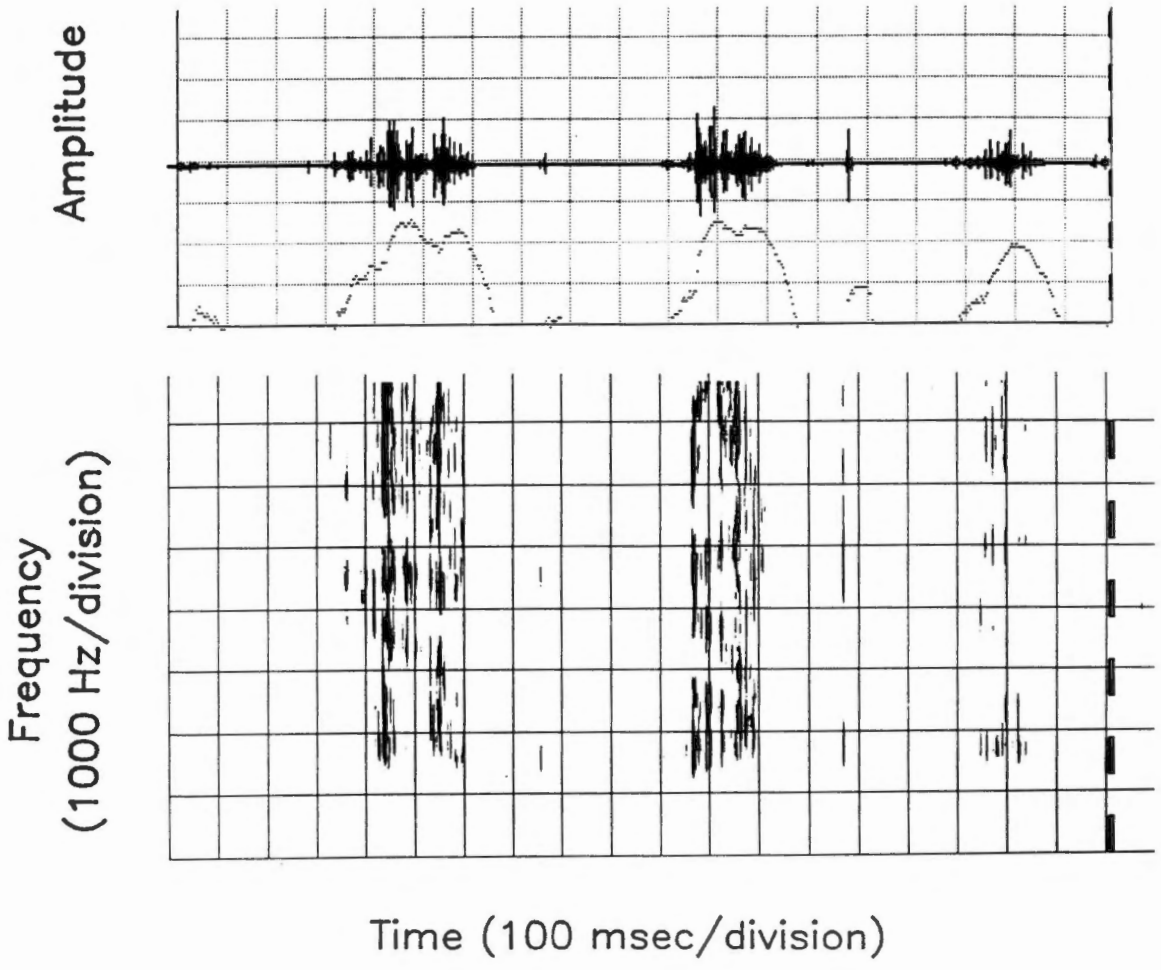


Figure IV.9 – Amplitude display (top) and wideband spectrogram (bottom) for the sounds of the initial 3 chews by subject 2 (adult female) for a raw carrot sample, 1.27 cm in diameter. Time (x-axis) proceeds from 0 to 2 sec from left to right (100 msec/vertical division). For the amplitude display, the y-axis indicates amplitude. Amplitude increases from bottom to top of the display. For the spectrogram, the y-axis indicates frequency which increases from 0 to 8000 Hz from bottom to top of the spectrogram (1000 Hz/horizontal division). Darkness of the spectrogram indicates amplitude with amplitude increasing as darkness increases.

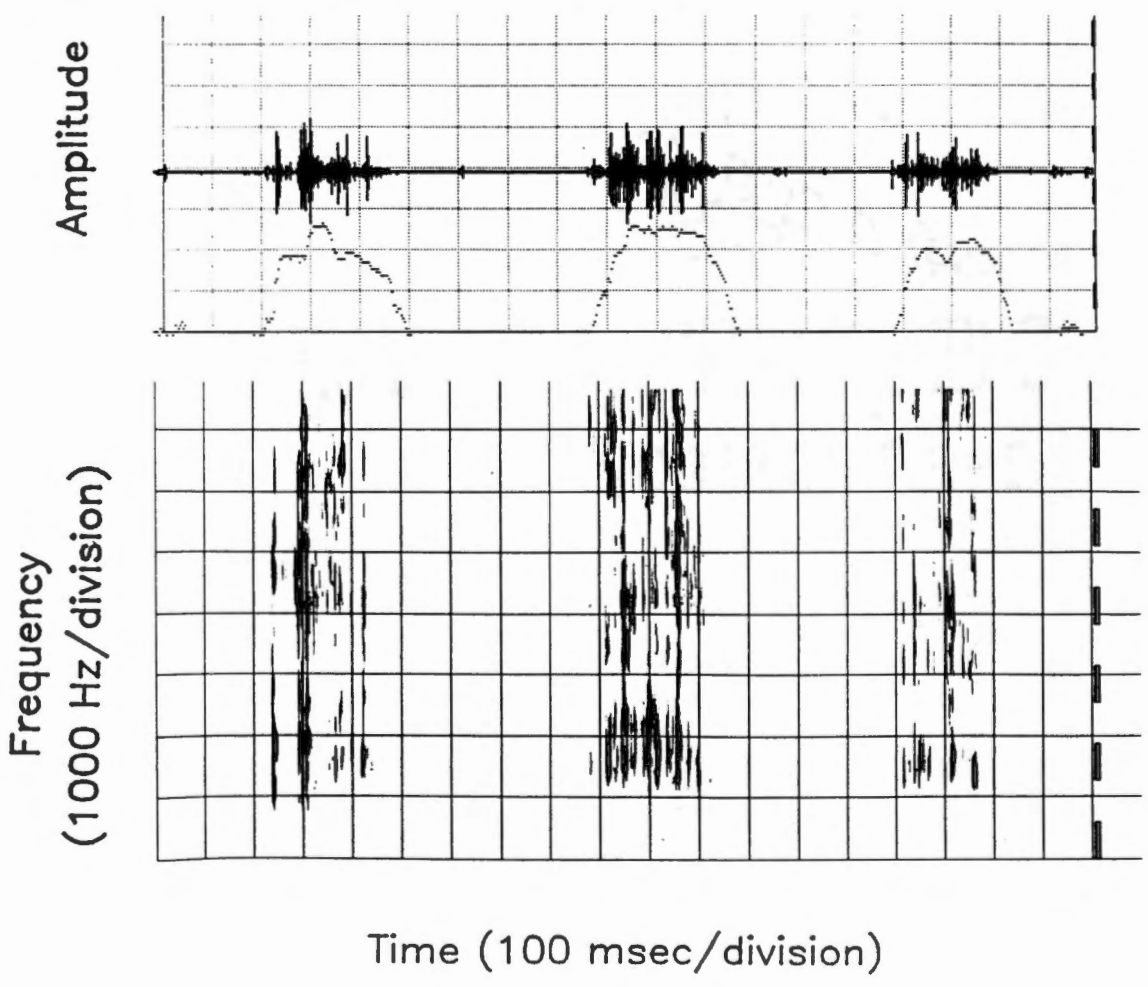


Figure IV.10 – Amplitude display (top) and wideband spectrogram (bottom) for the sounds of the initial 3 chews by subject 2 (adult female) for a raw carrot sample, 1.90 cm in diameter. Time (x-axis) proceeds from 0 to 2 sec from left to right (100 msec/vertical division). For the amplitude display, the y-axis indicates amplitude. Amplitude increases from bottom to top of the display. For the spectrogram, the y-axis indicates frequency which increases from 0 to 8000 Hz from bottom to top of the spectrogram (1000 Hz/horizontal division). Darkness of the spectrogram indicates amplitude with amplitude increasing as darkness increases.

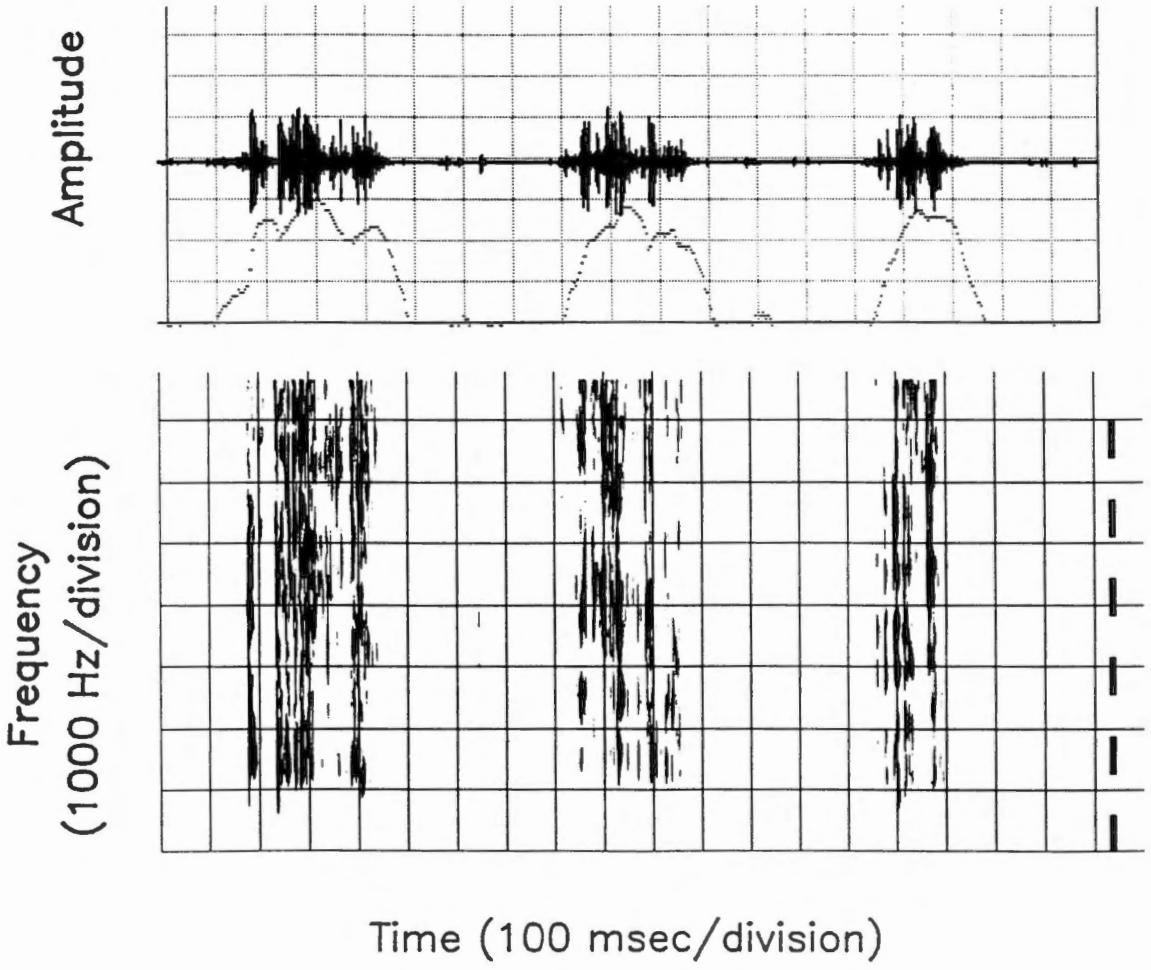


Figure IV.11 – Amplitude display (top) and wideband spectrogram (bottom) for the sounds of the initial 3 chews by subject 2 (adult female) for a raw carrot sample, 2.54 cm in diameter. Time (x-axis) proceeds from 0 to 2 sec from left to right (100 msec/vertical division). For the amplitude display, the y-axis indicates amplitude. Amplitude increases from bottom to top of the display. For the spectrogram, the y-axis indicates frequency which increases from 0 to 8000 Hz from bottom to top of the spectrogram (1000 Hz/horizontal division). Darkness of the spectrogram indicates amplitude with amplitude increasing as darkness increases.

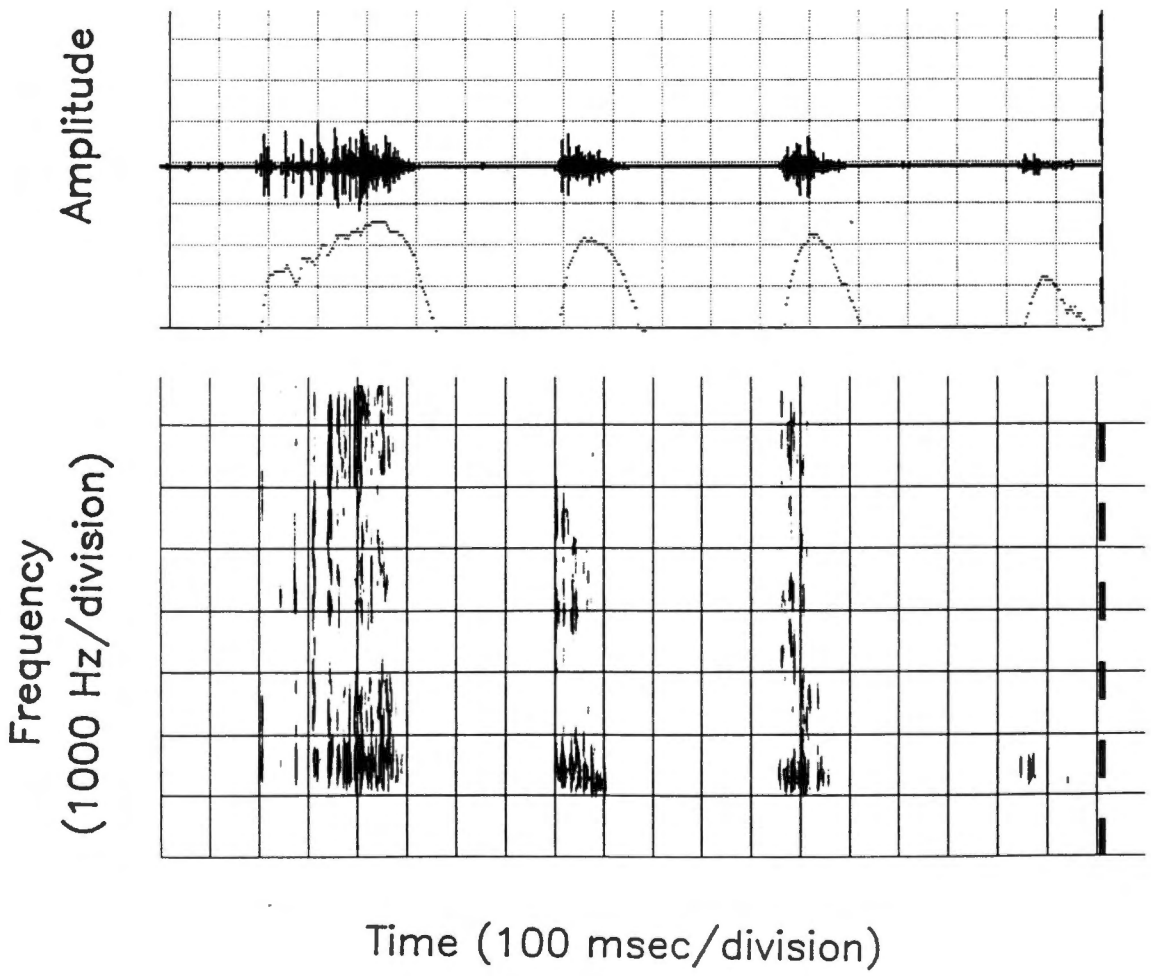


Figure IV.12 – Amplitude display (top) and wideband spectrogram (bottom) for the sounds of the initial 4 chews by subject 2 (adult female) for a teething toast sample, 1.27 cm in diameter. Time (x-axis) proceeds from 0 to 2 sec from left to right (100 msec/vertical division). For the amplitude display, the y-axis indicates amplitude. Amplitude increases from bottom to top of the display. For the spectrogram, the y-axis indicates frequency which increases from 0 to 8000 Hz from bottom to top of the spectrogram (1000 Hz/horizontal division). Darkness of the spectrogram indicates amplitude with amplitude increasing as darkness increases.

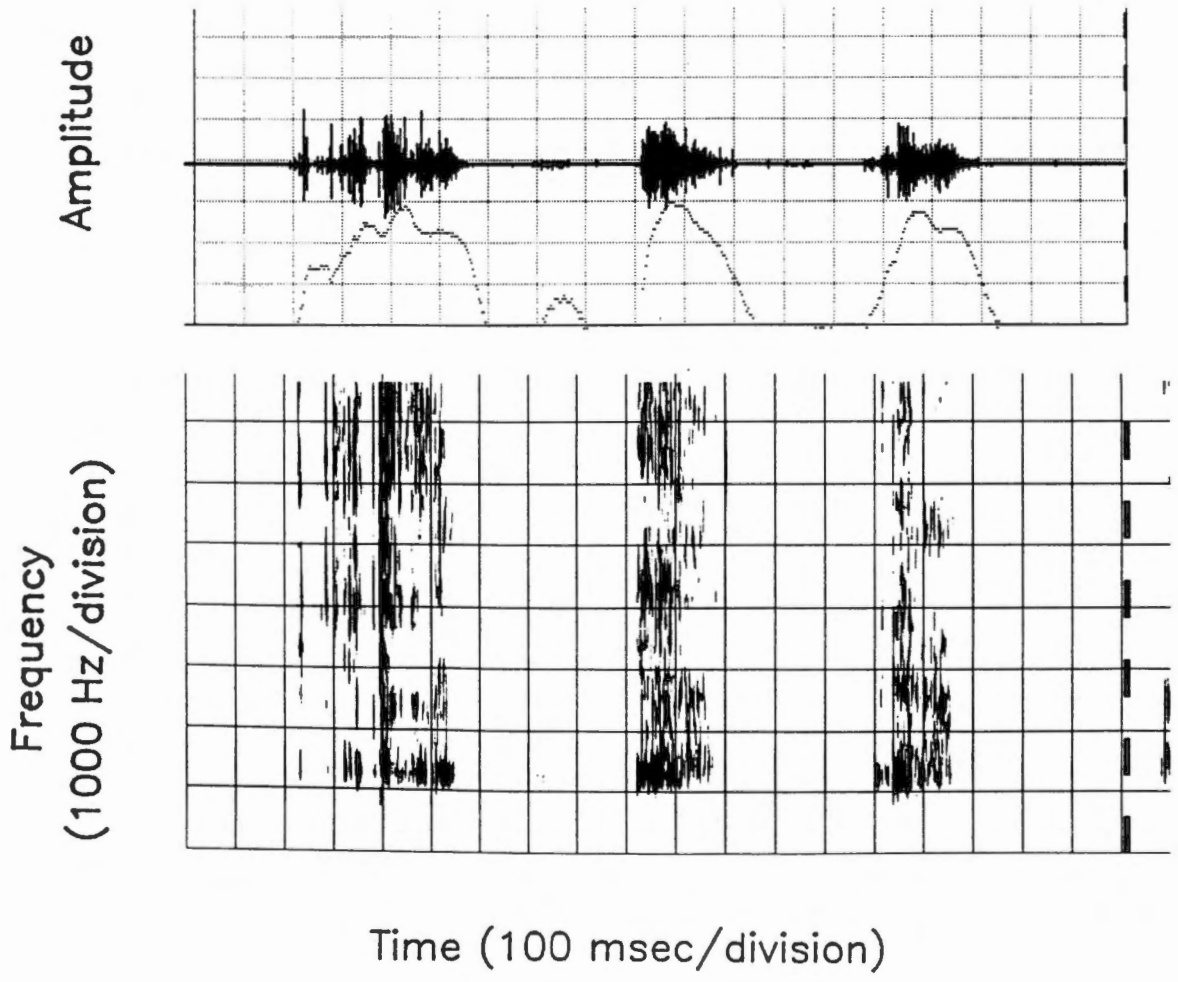


Figure IV.13 – Amplitude display (top) and wideband spectrogram (bottom) for the sounds of the initial 3 chews by subject 2 (adult female) for a teething toast sample, 1.90 cm in diameter. Time (x-axis) proceeds from 0 to 2 sec from left to right (100 msec/vertical division). For the amplitude display, the y-axis indicates amplitude. Amplitude increases from bottom to top of the display. For the spectrogram, the y-axis indicates frequency which increases from 0 to 8000 Hz from bottom to top of the spectrogram (1000 Hz/horizontal division). Darkness of the spectrogram indicates amplitude with amplitude increasing as darkness increases.

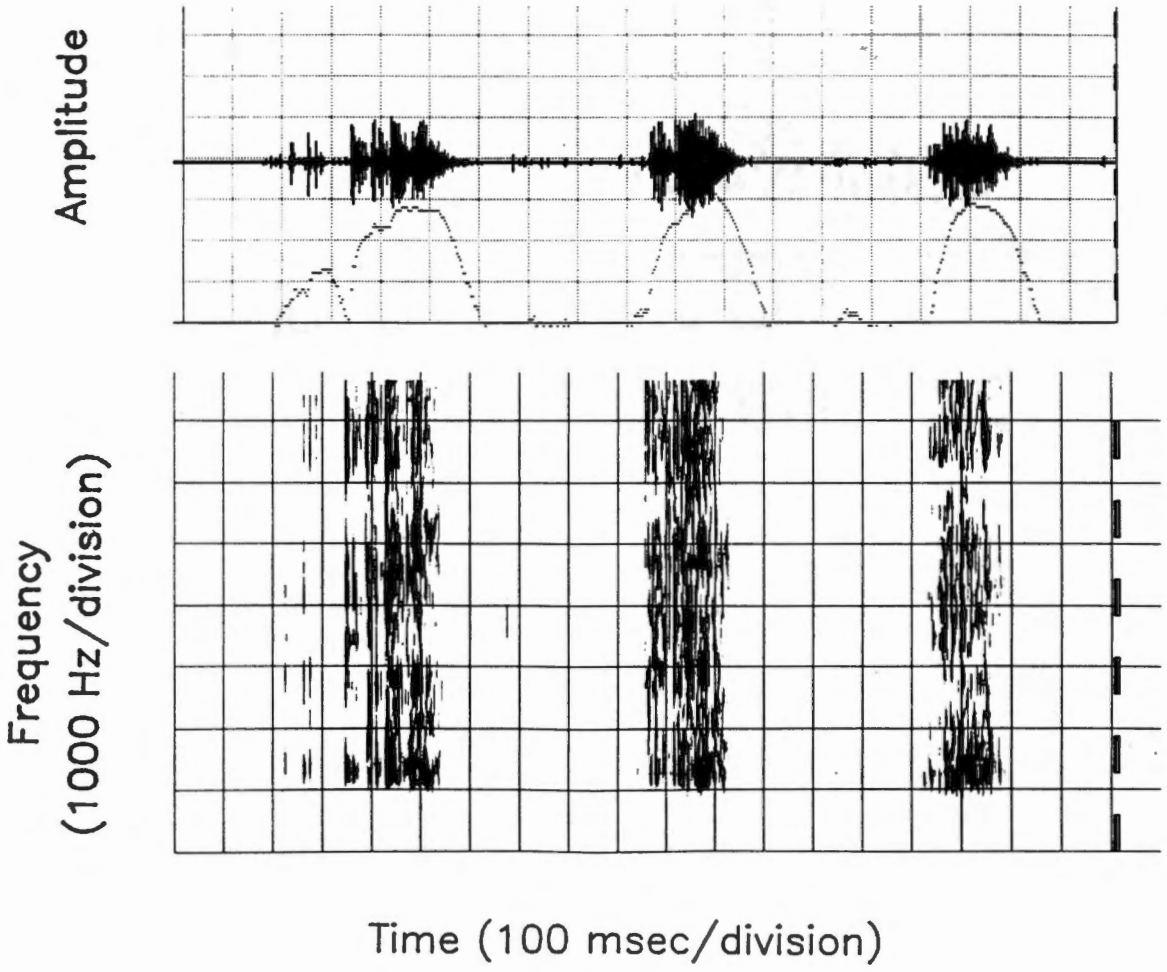


Figure IV.14 – Amplitude display (top) and wideband spectrogram (bottom) for the sounds of the initial 3 chews by subject 2 (adult female) for a teething toast sample, 2.54 cm in diameter. Time (x-axis) proceeds from 0 to 2 sec from left to right (100 msec/vertical division). For the amplitude display, the y-axis indicates amplitude. Amplitude increases from bottom to top of the display. For the spectrogram, the y-axis indicates frequency which increases from 0 to 8000 Hz from bottom to top of the spectrogram (1000 Hz/horizontal division). Darkness of the spectrogram indicates amplitude with amplitude increasing as darkness increases.

amplitude. Average power spectra of the sounds produced by subject 2 for the food samples are shown in Figures IV.15-IV.18. Spectra are shown for sounds of the initial 2 chews which were analyzed for the samples. Specifically, spectra are for the initial 100-msec segments of the sounds for each chew. In the spectra, the 8000-Hz range of frequencies used for analysis is shown along the x-axis. Frequency increases at the rate of 1000 Hz/vertical division from left to right of the spectra. Amplitude is shown along the y-axis. Peaks within the spectra correspond to the dark horizontal bands (formants) of the wideband spectrograms.

Wideband spectrograms indicate that for sounds of all food samples acoustic energy was present across the 8000-Hz range of frequencies. This range was used for analysis because it is the standard range for analysis of speech sounds (Perkins and Kent, 1986; Tosi, 1979). Average power spectra of the sounds indicate that acoustic energy was concentrated at the lower frequencies within the 8000-Hz range. The highest peak in the spectra for the sounds occurred within the region of 1000-2000-Hz. This peak represents the first formant of the sounds. Because acoustic energy was concentrated within the lower frequency regions of the spectra, only the first 5 formants of the sounds were measured.

Amplitude displays indicate that bursts occurred in the waveforms of sounds for the food samples. Whereas bursts occurred in waveforms for both chews of the carrot samples, bursts tended to occur primarily in the waveform for the first chew of the teething toast samples.

Similar results were obtained in the first experiment (Chapter III) of this study. Wideband spectrograms indicated that the first formant was the most prominent formant for sounds of foods which were reference standards for the hardness and fracturability scales for the Texture Profile Method (Muñoz, 1986; Szczesniak et al., 1963). Additionally, the first formant tended to occur within the frequency range of 1000-2000 Hz for sounds produced by 3 adult subjects. Waveforms also indicated that bursts characterized sounds of foods, such as raw carrot, which are reference standards for the hardness

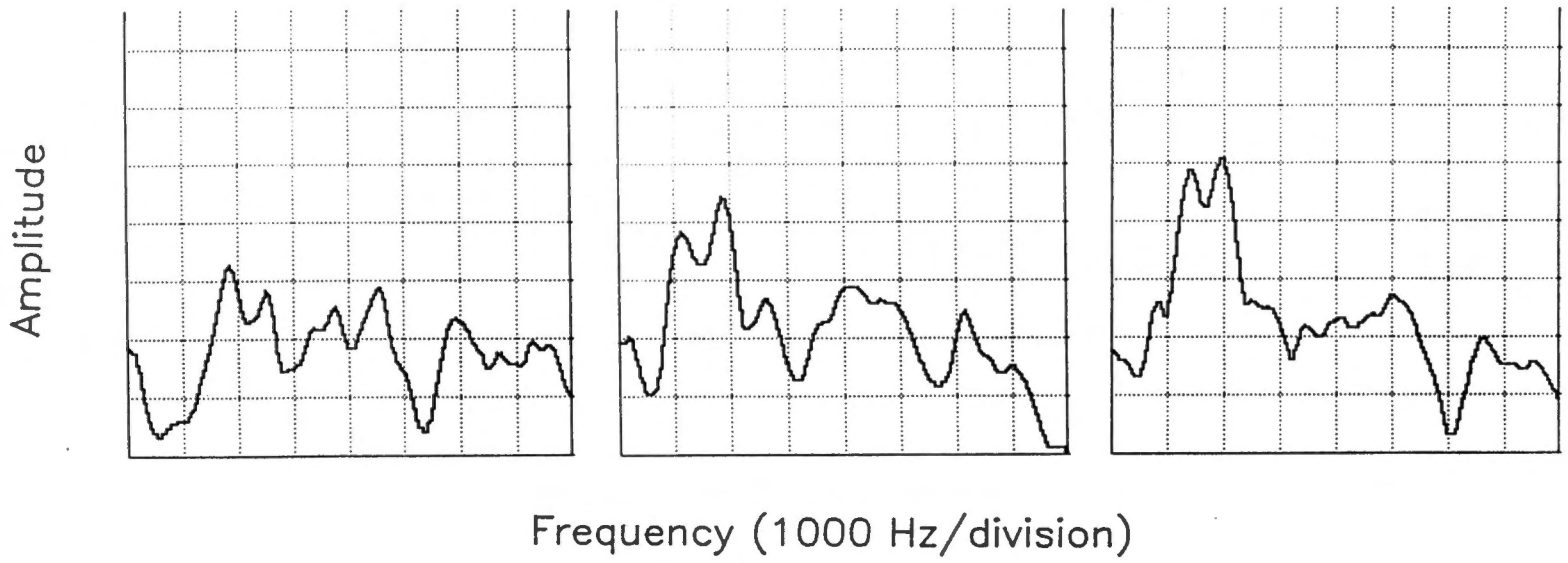


Figure IV.15 – Average power spectra for the sounds of the first chew by subject 2 (adult female) for raw carrot samples of the following diameters: 1.27 cm (left); 1.90 cm (center); and 2.54 cm (right). The x-axis indicates frequency and the y-axis indicates amplitude. Frequency increases from left to right of the spectra at the rate of 1000 Hz/horizontal division. Amplitude increases from bottom to top of the spectra.

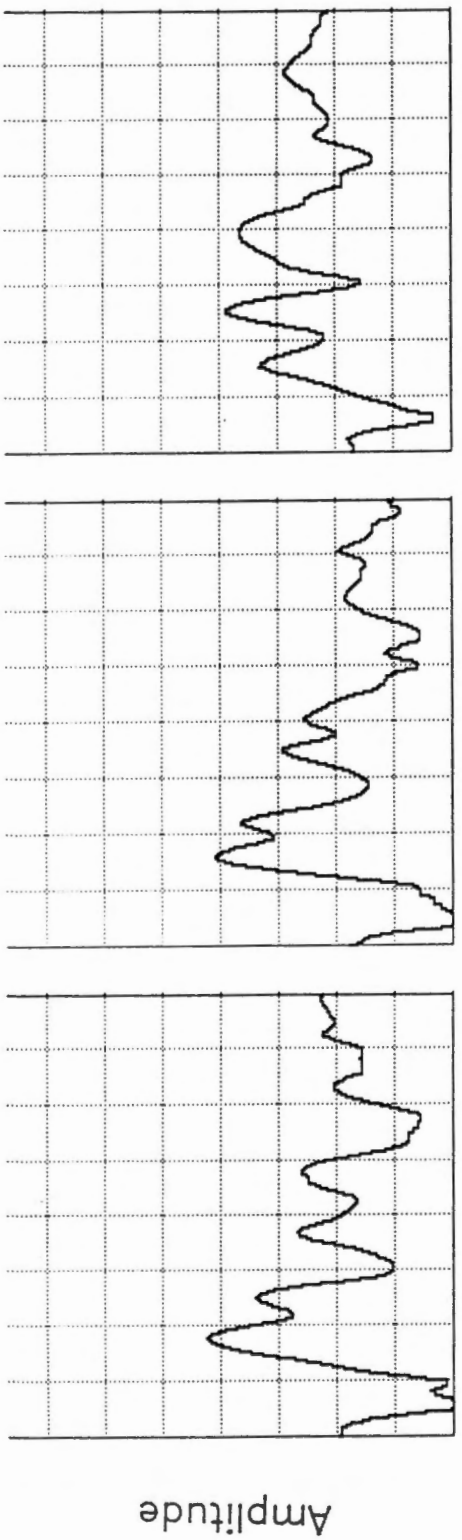


Figure IV.16 – Average power spectra for the sounds of the second chew by subject 2 (adult female) for raw carrot samples of the following diameters: 1.27 cm (left); 1.90 cm (center); and 2.54 cm (right). The x-axis indicates frequency and the y-axis indicates amplitude. Frequency increases from left to right of the spectra at the rate of 1000 Hz/horizontal division. Amplitude increases from bottom to top of the spectra.

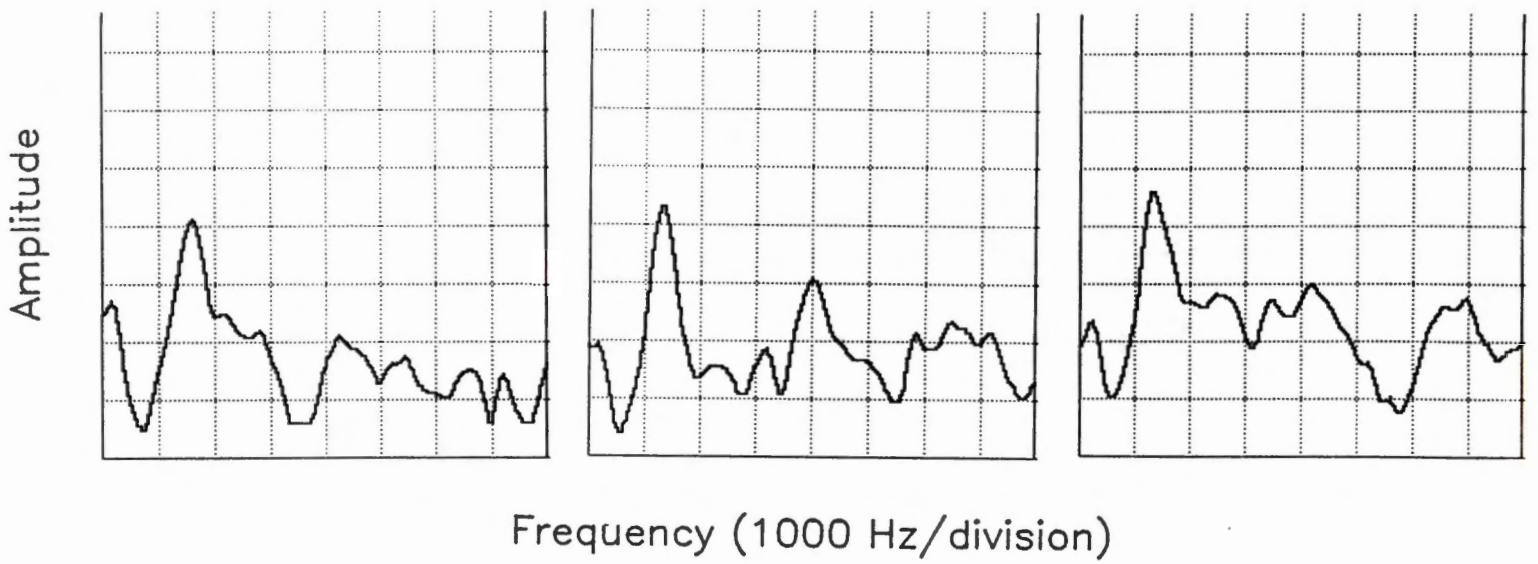


Figure IV.17 – Average power spectra for the sounds of the first chew by subject 2 (adult female) for teething toast samples of the following diameters: 1.27 cm (left); 1.90 cm (center); and 2.54 cm (right). The x-axis indicates frequency and the y-axis indicates amplitude. Frequency increases from left to right of the spectra at the rate of 1000 Hz/horizontal division. Amplitude increases from bottom to top of the spectra.

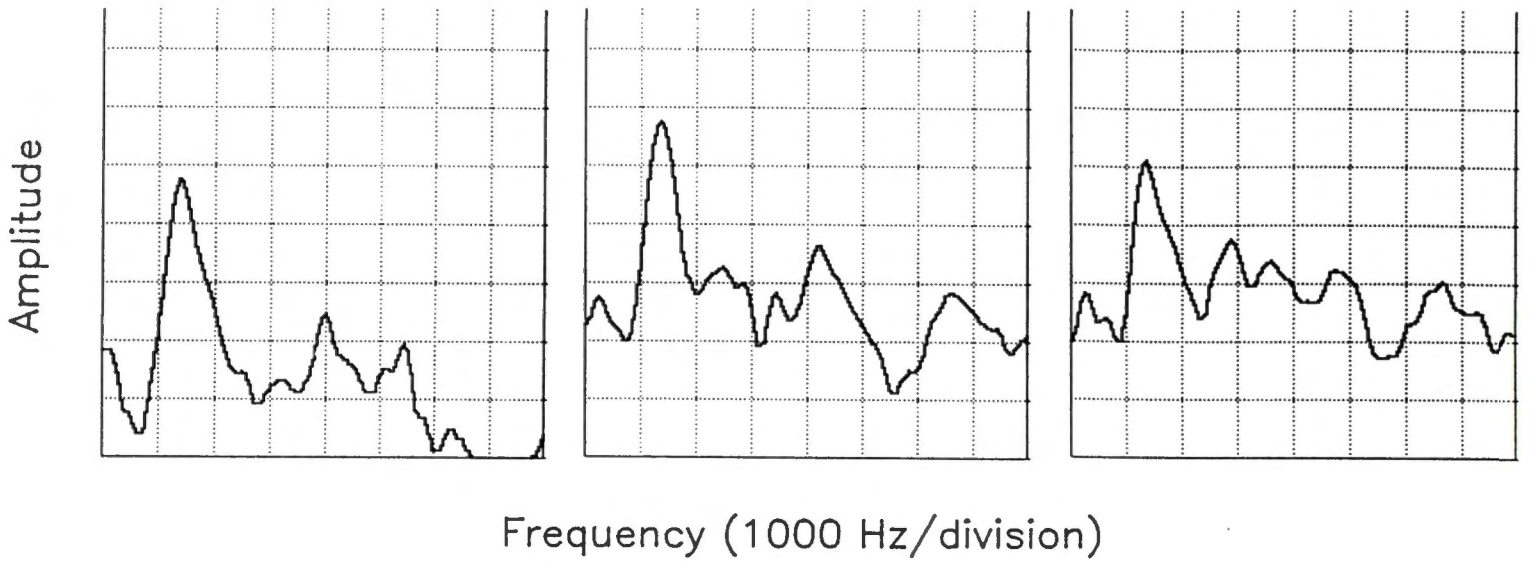


Figure IV.18 – Average power spectra for the sounds of the second chew by subject 2 (adult female) for teething toast samples of the following diameters: 1.27 cm (left); 1.90 cm (center); 2.54 cm (right). The x-axis indicates frequency and the y-axis indicates amplitude. Frequency increases from left to right of the spectra at the rate of 1000 Hz/horizontal division. Amplitude increases from bottom to top of the spectra.

scale. In contrast, acoustic energy was continuously distributed throughout sounds of chews for foods which are reference standards for the fracturability scale of the Texture Profile Method. Some of these foods included graham cracker and melba toast. These foods are similar to the teething toast samples used in this experiment in that they are dry porous foods. In comparison, the raw carrot samples are high moisture foods (Table IV.3).

Because results of the first experiment (Chapter III) indicated that acoustical characteristics of mastication sounds may vary with the individual, variation in measures of the characteristics was examined in relation to the 6 subjects in this experiment. Although reports of variation in acoustical measures of mastication sounds are nonexistent in the food science literature, researchers have indicated that variation in acoustical measures can be expected because of the nature of the sources (Drake, 1963; 1965b; Lee et al., 1988, 1990). In addition to variation in the properties of food samples, Lee et al. (1988, 1990) reported sources which relate to physiological characteristics of individuals. These sources included oral status, rate of salivation, and manner and magnitude of force applied to food samples during mastication.

Intrasubject Variability in Acoustical Measures of Mastication Sounds

From the analysis of the sounds produced by the 6 subjects in this experiment, inferences were to be made concerning the effects of the diameter of food samples on the acoustical characteristics of mastication sounds for foods differing in physical properties. However, the type of inferences that can be made from any experiment depends on the nature of the data, particularly the variability in the data (Cochran and Cox, 1957). Therefore, variation in acoustical measures of the sounds produced by the 6 subjects was examined. Both intrasubject and intersubject variability in acoustical measures were examined.

This section pertains to the intrasubject variability in acoustical measures of sounds for the initial 2 chews of the food samples. Specifically, the objective was to determine if there were differences in intrasubject variation among the 6 subjects. In other words, was the variation within subjects consistent across subjects. To test for this consistency, or homogeneity, variances of the acoustical measures were calculated and used as estimates of variation in the statistical analyses. Both variances and ranks of the variances were analyzed to test for homogeneity.

Statistical analysis

In this discussion, data sets refer to the data obtained from acoustical analyses. Four data sets were analyzed statistically. Data sets included amplitude display parameters, formant parameters, and duration parameters. Formant and duration parameters were obtained from average power spectra and/or wideband spectrograms. Additionally, data from oscilloscopic analysis of the mastication sounds were analyzed. Although the results of the analysis are presented in this section, the results are not discussed because of the lack of precision in the acoustical method.

In general, the design of this experiment was a 6 x 2 x 3 factorial design with subject (6 levels), type of food (2 levels), and diameter of the food samples (3 levels) as the factors. Although the acoustical characteristics of the sounds for the 2 initial chews were analyzed, chew was not a factor in the experiment. Therefore, separate statistical analyses were performed on the acoustical measures for the 2 chews. Chew was not treated as a factor in this experiment because differences were expected in the acoustical characteristics of the sounds for the chews. Differences were attributed to the breakdown of the food sample during the first chew. This breakdown changes the physical properties of the samples for the second chew. However, the 2 chews were examined because researchers have suggested that the sounds of the initial chews of foods may be more important than those of subsequent chews in the assessment of

food texture, particularly crispness and crunchiness (Lee et al., 1988; Christensen and Vickers, 1981).

Proc SUMMARY was used to compute the standard deviations of each of the acoustical measures. Standard deviations were calculated over 10 repetitions within a subject for each food type and sample diameter. From the standard deviations, variances were calculated and used as estimates of variation for analysis. Proc GLM was used for analysis of variance of the estimates. Because interest was in the variation of subjects in this experiment, a fixed-effects model was assumed. Main effects included subject, type of food (food), and diameter of the sample (size). Additionally, the subject x food, subject x size, and size x food interactions were tested.

Similar statistical procedures were used for analysis of the ranks of the variances. However, once the variances were calculated, Proc RANK was used to rank the variances. The ranks then were used as the estimates of variation for analysis. Proc GLM was used for analysis of the estimates.

Because the estimates of variation were calculated over 10 repetitions within a subject for each food type and sample diameter, intrasubject variability could be evaluated. When subject was a significant source of variation, this indicated that the variation within subjects (intrasubject variability) was inconsistent across subjects. When food, size, and the two-way interactions were significant sources, this indicated that the sources contributed significantly to the variation in acoustical measures.

Analysis of variances

Results of the analyses of variances are presented in the ANOVA Tables B.3-B.7 in Appendix B. Although the 2 chews were analyzed separately, results for the 2 chews are presented in the same table. Summaries of the significant sources of variation for each acoustical measure are presented in Tables IV.11-IV.15.

In general, results indicate that many factors affected the variances; however, the extent to which the variances were affected depended on the acoustical measure. For the amplitude display

Table IV.11 – Significant sources of variation in estimates of variation for amplitude display parameters for sounds of the initial 2 chews of food samples

Estimate of variation Source	Chew	Parameter		
		Duration	Peak amplitude	Average amplitude
Variance	1			
Size				
Food				
Size*Food				
Subject		**		
Size*Subject				
Food*Subject				
Ranks of variance	1			
Size				
Food				
Size*Food				
Subject		**		
Size*Subject				
Food*Subject				
Variance	2			
Size		**	**	
Food				
Size*Food				
Subject		**		
Size*Subject				
Food*Subject				
Ranks of variance	2			
Size		**	**	*
Food			*	
Size*Food				
Subject		**		
Size*Subject				
Food*Subject				*

* $p < 0.05$.
** $p < 0.01$.

Table IV.12 – Significant sources of variation in estimates of variation for duration parameters of sounds for the initial 2 chews of food samples

Form of variance Source	Parameter				
	Chew 1	Chew 2	Onset	Between chews	Total
Variance					
Size		*	*		
Food	*			**	
Size*Food					
Subject		**	**	**	**
Size*Subject			**		
Food*Subject			*		
Ranks of variance					
Size		*			
Food	*			**	
Size*Food					
Subject		**	**	**	**
Size*Subject					
Food*Subject					

* $p < 0.05$.
** $p < 0.01$.

Table IV.13 – Significant sources of variation in estimates of variation for formant (F1-F5) frequencies of sounds for the 2 initial chews of food samples

Estimate of variation Source	Chew	Formant F1	F2	F3	F4	F5
Variance	1					
Size						
Food		*				
Size*Food				*		
Subject					*	
Size*Subject						
Food*Subject						
Ranks of variance	1					
Size			*			
Food		**				
Size*Food			**	**		
Subject		*		**	**	*
Size*Subject						
Food*Subject						
Variance	2					
Size						
Food					*	
Size*Food						
Subject					**	
Size*Subject						
Food*Subject						
Ranks of variance	2					
Size						
Food				**	**	
Size*Food				**		
Subject					**	**
Size*Subject						
Food*Subject						

* $p < 0.05$.
** $p < 0.01$.

Table IV.14 – Significant sources of variation in estimates of variation for formant (F1-F5) amplitudes of sounds for the 2 initial chews of food samples

Estimate of variation Source	Chew	Formant F1	F2	F3	F4	F5
Variance	1					
Size				*		
Food				*		**
Size*Food						
Subject		*				
Size*Subject						
Food*Subject				*		
Ranks of variance	1					
Size				*		
Food				**		**
Size*Food						
Subject						
Size*Subject						
Food*Subject						
Variance	2					
Size						
Food		**				
Size*Food						
Subject						
Size*Subject						
Food*Subject						
Ranks of variance	2					
Size						
Food		**	**			
Size*Food						
Subject						
Size*Subject						
Food*Subject						

* $p < 0.05$.
** $p < 0.01$.

Table IV.15 – Significant sources of variation in estimates of variation for oscilloscopic parameters of sounds for the 2 initial chews of food samples

Estimate of variation Source	Chew	Parameter		
		Duration	Peak time	Peak amplitude
Variance	1			
Size		*		
Food		**		
Size*Food				
Subject		**		*
Size*Subject		*		
Food*Subject				
Ranks of variance	1			
Size		*		
Food		*	*	
Size*Food				
Subject		**	**	**
Size*Subject		*	**	*
Food*Subject			*	
Variance	2			
Size		**		*
Food			*	
Size*Food				
Subject		**	**	
Size*Subject				
Food*Subject				
Ranks of variance	2			
Size		*		**
Food				
Size*Food				
Subject		**	**	
Size*Subject			*	
Food*Subject			*	

* $p < 0.05$.
** $p < 0.01$.

parameters (Table IV.11), few sources significantly affected the variances for either the first or second chew. In particular, none of the sources significantly affected the variation in average amplitude of the mastication sounds for the first and the second chew. Results were similar for the peak amplitude of the sounds for the first chew. However, type of food contributed significantly to the variation in peak amplitude of sounds for the second chew, indicating differences in variation in peak amplitude of sounds for the second chew of the 2 types of food. Diameter of the food samples also affected the variation in duration of sounds for the second chew, indicating differences in variation in duration of sounds for the second chew for the 3 diameters of the samples. Subject also had a significant effect on the duration of the sounds for the first and second chew. Therefore, the variation in duration of sounds within subjects was not consistent for the 6 subjects in the experiment.

Variation in measures of duration (Table IV.12) was expected based on the results of the first experiment (Chapter III) of the study. Descriptive information from the experiment indicated that the durations of sounds produced by 3 adult subjects (1 male, 2 females) differed in duration. Differences were attributed to differences in chewing rates of the subjects. In this experiment, results indicate that many factors affected the variances of the duration parameters. In particular, subject was a significant source for all duration parameters, except chew 1, indicating that intrasubject variability was inconsistent. Additionally, sample diameter, food type, and two-way interactions contributed to the variation in some of the duration parameters; however, trends were not observed in the effects of these factors on the parameters.

For the formant parameters (F1-F5), subject and type of food contributed significantly to the variation in the frequencies and amplitudes of the formants (Tables IV.13 and IV.14). Subject affected the variation in the frequency of F4 for both the first and second chew. Subject also affected the the variation in the amplitude of F1 for the first chew. These results indicate that intrasubject variability was inconsistent for these measures. Type

of food was a significant source of variation in the frequency of F1 and the amplitude of F3. For the second chew, type of food contributed to the variation in the frequency of F4 and the amplitude of F1.

A consistent intrasubject variation is essential for analysis of variance of the means of the acoustical measures. Analysis of variance of the means would provide information which could be used to make inferences concerning the effects of the diameter of food samples on acoustical measures of mastication sounds for foods differing in physical properties. One of the assumptions for use of analysis of variance is equality of variances. Populations, in this case subjects, from which samples are taken must have equal variances. Equality of variance is assumed because between-sample mean squares are compared with within-sample mean squares to determine significant differences between population means (Remington and Schork, 1970; Sokal and Rohlf, 1969).

Results of the analysis of the variances indicated a lack of consistency in intrasubject variation. Additionally, other factors, particularly type of food and diameter of the sample, contributed significantly to the variation. Therefore, the variances were converted to ranks, and the ranks then were used as estimates of variation to test the consistency of intrasubject variation. Variances were transformed to ranks to try to meet the assumption of equality of variances (Bartlett, 1947; Sokal and Rohlf, 1969).

Analysis of ranks

Results of the analyses of variances of ranked variances are presented in the ANOVA Tables B.8-B.12 in Appendix B. Mean squares and probability values for the sources of variation are indicated in the tables. Summaries of the results were presented along with those for the analyses of the variances in Tables IV.11-IV.15.

For the amplitude display parameters, results were similar to those for analysis of the variances. In particular, results were the same for measures of the first chew. For the second chew, no changes occurred in the effect of subject on the ranks of the variances.

Duration, again, was the only parameter for which subject had a significant effect, indicating that intrasubject variability was inconsistent for the subjects. In contrast, size (sample diameter) and the food x subject interaction were significant sources of variation in the average amplitude of the sounds for the second chew. Additionally, type of food contributed to the variation in the peak amplitude of sounds for the second chew.

For the duration parameters (Table IV.12), results were similar to those for analysis of the variances. Subject was a significant source of variation for all parameters, except chew 1, indicating that intrasubject variability in the duration of the sounds was inconsistent for the subjects.

Differences occurred between the two types of analyses for measures of frequencies of the formants (Table IV.13). Transformation of variances to ranks increased the number of sources which significantly affected the formants for the first chew. In particular, subject significantly affected the variation in the frequencies of formants F1, F3, F4, and F5, indicating that transformation increased the inconsistency in intrasubject variation. A similar change occurred in the frequency of F5 for the second chew.

For amplitude of the formants (Table IV.14), results were similar to those for analysis of the variances. Subject did not significantly affect the variation in the amplitude of the formants, indicating a consistency in intrasubject variation. However, transformation tended to reduce the number of other sources that contributed to the variation in formant amplitudes for the first chew.

Summary

In summary, results of the analysis of the variances and ranks of the variances indicate that many factors affected the variation in acoustical measures. However, the main effects, in the statistical model, including subject, type of food, and diameter of the sample, were significant sources of variation more often than the two-way interactions. Although some differences occurred between the two

types of analyses, transformation did not reduce the number of sources that affected the variation in the data. Additionally, no trend in the effect of transformation was observed across all of the acoustical measures.

Intersubject Variability in Acoustical Measures of Mastication Sounds

Proc VARCOMP, a variance component technique, was used to examine the intersubject variability in acoustical measures of the sounds produced by the 6 subjects. The maximum-likelihood (ML) method was used to estimate the components of variance (SAS Institute, Inc., 1985). For analysis, a random-effects model was assumed with subject as the main effect. Estimates were calculated over 60 repetitions for each food sample (food type/sample diameter). Subject and error were the variance components which were estimated. Because subject was the only main effect in the model, the subject component was an estimate of intersubject variability, and the error component was an estimate of intrasubject variability. Variance components were estimated for all acoustical measures. Data for the 2 chews of the food samples were analyzed separately.

Maximum-likelihood estimates of the variance components are presented in Tables IV.16-IV.20. For each acoustical measure, estimates are shown for each combination of food type and sample diameter. Additionally, estimates for the 2 chews are presented in the same tables.

In general, the VARCOMP procedure is designed to estimate variance components for general linear models with random effects. The assumptions for use of the procedure are the same as those for use of analysis of variance. This includes the assumption that the populations (subjects) which are sampled have equal variances (Gagula and Singh, 1984; SAS Institute, Inc., 1985). However, analysis of the estimates of variation in the acoustical measures indicated an inconsistent intrasubject variability. Therefore, the VARCOMP procedure was used only to assess whether the intersubject

Table IV.16 – Maximum-likelihood estimates of variance components for amplitude display parameters of sounds for the initial 2 chews of the food samples

Parameter Food	Chew	Variance component	Diameter (cm) of sample 1.25	1.88	2.50
Peak amplitude					
Carrot	1	Subject	1.15	2.59	1.22
		Error	5.50	2.77	2.49
Teething toast	1	Subject	1.74	0.88	2.18
		Error	1.61	2.97	1.95
Carrot	2	Subject	0.65	0.67	2.27
		Error	11.67	4.47	5.18
Teething toast	2	Subject	4.65	1.00	2.61
		Error	10.46	2.70	2.04
Average amplitude					
Carrot	1	Subject	4.36	10.86	7.05
		Error	8.22	8.32	10.34
Teething toast	1	Subject	4.27	2.55	1.68
		Error	6.09	8.14	5.15
Carrot	2	Subject	0.87	0.28	3.18
		Error	12.90	14.91	8.36
Teething toast	2	Subject	2.12	4.67	0.99
		Error	11.06	5.78	9.58
Duration of chew					
Carrot	1	Subject	8095	6044	3833
		Error	6177	5363	10250
Teething toast	1	Subject	5034	5392	4689
		Error	8309	11734	15942
Carrot	2	Subject	2664	3011	2232
		Error	2163	3320	5857
Teething toast	2	Subject	7539	3049	4234
		Error	1489	3549	5040

Table IV.17 – Maximum-likelihood estimates of variance components for formant amplitudes (F1-F5) of sounds for the initial 2 chews of the food samples

Formant			Diameter (cm) of sample		
Food	Chew	Variance component	1.25	1.88	2.50
F1					
Carrot	1	Subject	8.02	2.62	0.00
		Error	16.73	17.52	18.04
Teething toast	1	Subject	1.63	10.39	11.95
		Error	13.52	13.91	14.06
Carrot	2	Subject	5.63	2.19	1.08
		Error	21.00	25.64	23.44
Teething toast	2	Subject	7.34	1.13	4.44
		Error	16.53	9.28	13.59
F2					
Carrot	1	Subject	14.97	39.20	14.22
		Error	22.31	9.89	24.79
Teething toast	1	Subject	16.92	31.51	16.81
		Error	12.86	15.89	8.84
Carrot	2	Subject	0.00	12.74	7.85
		Error	28.87	17.94	23.33
Teething toast	2	Subject	10.43	5.37	12.78
		Error	14.35	12.29	18.48
F3					
Carrot	1	Subject	3.24	10.22	5.78
		Error	20.60	14.33	15.73
Teething toast	1	Subject	8.06	9.56	13.49
		Error	15.17	12.45	9.02
Carrot	2	Subject	2.30	0.68	2.41
		Error	15.05	14.93	18.67
Teething toast	2	Subject	4.68	7.17	10.76
		Error	17.22	7.98	8.96

continued

Table IV.17 – (continued)

Formant Food	Chew	Variance component	Diameter (cm) of sample 1.25	1.88	2.50
F4					
Carrot	1	Subject	1.67	3.64	0.01
		Error	11.53	11.21	16.39
Teething toast	1	Subject	4.93	2.29	3.49
		Error	9.40	15.46	8.63
Carrot	2	Subject	4.45	1.92	2.46
		Error	13.42	14.26	11.10
Teething toast	2	Subject	1.30	4.82	0.44
		Error	13.97	8.93	10.14
F5					
Carrot	1	Subject	0.96	0.75	3.37
		Error	11.27	11.05	16.45
Teething toast	1	Subject	1.75	4.50	7.68
		Error	6.95	7.56	8.47
Carrot	2	Subject	0.00	1.41	0.83
		Error	12.53	10.01	11.06
Teething toast	2	Subject	2.01	0.94	3.34
		Error	8.45	8.56	8.05

Table IV.18 – Maximum-likelihood estimates of variance components for formant frequencies (F1-F5) of sounds for the initial 2 chews of the food samples

Formant / Food	Chew	Variance component	Diameter (cm) of sample 1.25	1.88	2.50
F1					
Carrot	1	Subject	24381	8487	5555
		Error	15262	8804	10404
Teething toast	1	Subject	13727	19706	22290
		Error	3452	6006	6477
Carrot	2	Subject	24147	7356	9066
		Error	13718	11597	12512
Teething toast	2	Subject	9432	13484	11727
		Error	6299	6962	9739
F2					
Carrot	1	Subject	11760	45534	18457
		Error	139783	24397	56497
Teething toast	1	Subject	64660	23056	93168
		Error	41028	68035	54273
Carrot	2	Subject	3606	49947	30961
		Error	202749	48906	74048
Teething toast	2	Subject	44583	48013	33087
		Error	48217	39479	93973
F3					
Carrot	1	Subject	86557	60630	0
		Error	86931	33369	95159
Teething toast	1	Subject	129043	38851	81531
		Error	27544	117292	39615
Carrot	2	Subject	112519	56797	0
		Error	186005	53512	108374
Teething toast	2	Subject	104528	90019	144055
		Error	66773	51613	25476

continued

Table IV.18 – (continued)

Formant Food	Chew	Variance component	Diameter (cm) of sample 1.25	1.88	2.50
F4					
Carrot	1	Subject	84556	57560	11809
		Error	162311	106826	106981
Teething toast	1	Subject	161045	34160	92868
		Error	86361	128690	63229
Carrot	2	Subject	217629	101777	17500
		Error	213573	128901	226290
Teething toast	2	Subject	108271	63717	132662
		Error	140218	130603	80465
F5					
Carrot	1	Subject	129313	85888	21414
		Error	171732	108322	132024
Teething toast	1	Subject	201904	136468	220023
		Error	95997	164907	98469
Carrot	2	Subject	213023	94677	50600
		Error	123019	106273	168316
Teething toast	2	Subject	191905	163328	236955
		Error	145262	120976	411017

Table IV.19 – Maximum-likelihood estimates of variance components for duration parameters of sounds for the initial 2 chews of the food samples

Parameter Food	Variance component	Diameter (cm) of sample 1.25	1.88	2.50
Duration of chew 1				
Carrot	Subject	6851	4697	4122
	Error	4252	4655	6500
Teething toast	Subject	4665	5708	14518
	Error	9325	10908	16867
Duration of chew 2				
Carrot	Subject	2260	2130	2606
	Error	1792	1725	3686
Teething toast	Subject	5292	1863	2493
	Error	1420	2897	2614
Time from end of chew 1 to onset of chew 2				
Carrot	Subject	12768	2762	0
	Error	12357	10765	14977
Teething toast	Subject	9858	7519	1125
	Error	5984	4635	3844
Time from onset of chew 1 to onset of chew 2				
Carrot	Subject	52132	16338	3068
	Error	21623	14706	31693
Teething toast	Subject	25155	21432	23451
	Error	21160	17177	22629
Time from onset of chew 1 to end of chew 2				
Carrot	Subject	76522	30436	11334
	Error	21253	17953	39021
Teething toast	Subject	51331	32803	37016
	Error	21213	22887	22968

Table IV.20 – Maximum-likelihood estimates of variance components for oscilloscopic parameters of sounds for the initial 2 chews of the food samples

Parameter / Food	Chew	Variance component	Diameter (cm) of sample 1.25	1.88	2.50
Duration of chew					
Carrot	1	Subject	5272	2979	2730
		Error	3249	3965	6960
Teething toast	1	Subject	4613	4442	4873
		Error	7021	5911	10632
Carrot	2	Subject	1873	1813	282
		Error	1527	2252	4899
Teething toast	2	Subject	3249	1955	3452
		Error	1322	2468	3912
Peak time					
Carrot	1	Subject	1131	361	1744
		Error	2299	2592	3670
Teething toast	1	Subject	3148	2859	2638
		Error	3917	3480	6416
Carrot	2	Subject	0	673	112
		Error	2738	1894	3209
Teething toast	2	Subject	2024	772	97
		Error	1608	1858	2415
Peak amplitude					
Carrot	1	Subject	1.21	0.75	0.34
		Error	0.98	0.64	0.41
Teething toast	1	Subject	0.84	0.86	0.97
		Error	0.75	1.16	0.52
Carrot	2	Subject	0.75	1.02	0.83
		Error	4.69	1.55	1.68
Teething toast	2	Subject	3.34	0.55	1.23
		Error	5.76	2.05	1.26

variability was greater than or less than the intrasubject variability (Sanders, 1990).

For most acoustical measures, estimates of the intrasubject (error) component were greater than the estimates of the intersubject (subject) component. This trend occurred in estimates for both chews. In particular, it occurred in estimates for parameters of the amplitude display and for measures of formant amplitudes (Table IV.16 and IV.17). Variation in measures of amplitude was expected based on the results of the first experiment (Chapter III) of the study. Descriptive information indicated that the amplitude of waveforms of mastication sounds varied for 3 adult subjects (1 male, 2 females). Results of this experiment, however, indicate that intrasubject variation was greater than intersubject variation in measures of amplitude of the mastication sounds produced by the 6 subjects.

In contrast, estimates of the intersubject component were greater than estimates of the intrasubject component in approximately half of the cases for the formant frequencies and for the duration parameters (Tables IV.18 and IV.19). For formant frequencies (F1-F5), this trend occurred more frequently for the teething toast samples than for the carrot samples. For the duration parameters, however, this trend occurred for sample diameters of 1.27 and 1.90 cm.

Results of the analyses of variability in acoustical measures of the mastication sounds emphasize the need to stabilize the intrasubject variation in these measures. Not only was the intrasubject variation inconsistent for the 6 subjects, but also it was greater than the intersubject variation for most acoustical measures. Subject, type of food, and diameter of the sample were factors that influenced the variation. In general, these results indicate the highly variable nature of the masticatory act.

Dental researchers have reported on the variable nature of mastication. Ramfjord and Ash (1983) stated that masticatory stress varies within an individual and that this stress also increases toward the end of an individual's chewing sequence. Furthermore, the researchers reported that the type of food and habitual chewing

patterns of an individual influence the activities of the jaw muscles which control the masticatory act (Ramfjord and Ash, 1983). Ash (1984) stated that the type of occlusion, presence of dysfunction, and kind of food are factors that affect the speed, duration, and form of the chewing cycle. However, Ash (1984) also stated that although variation can be expected between consecutive strokes of an individual's chewing cycle, subsequences can be characteristics for an individual. For example, the average number of masticatory strokes is consistent for an individual (Ramfjord and Ash, 1983).

Effects of Diameter of Food Sample and Type of Food on Acoustical Measures of Mastication Sounds

In this section, factors that influenced acoustical measures of the mastication sounds are discussed. Although the effect of sample diameter is emphasized, the effects of type of food and subject producing the sounds also are discussed. The effects of these factors on both the means and variances of the acoustical measures are included in the discussion.

Statistical analysis

Because intrasubject variation in acoustical measures of the mastication sounds was inconsistent, data were transformed to ranks for analysis. Data were transformed to ranks for validity of the significance tests used in the statistical analysis (Bartlett, 1947; Sanders, 1990). Data for the 2 chews of the food samples were analyzed separately. First Proc RANK was used to convert the data to ranks. Next, Proc GLM was used for analysis of means of the ranks of the acoustical measures (SAS Institute, Inc., 1985). Means were calculated over 10 repetitions per subject for each type of food and diameter of sample. For analysis, a mixed-effects model was assumed with subject, type of food (food), and diameter of sample (size) as the main effects. Food type and sample diameter were fixed effects, and subject was the random effect in the model because inferences were to be made from the results for the 6 subjects in the experiment

(O'Mahony, 1986). Additionally, the food x size, size x subject, food x subject, and food x size x subject interactions were tested. In the analysis, F-values were calculated and used to determine significance of the main effects and interactions as sources of variation. In calculating the F-values, mean squares used as the denominator for each source were those indicated by O'Mahony (1986) for a 3-factor mixed-effects model (Tables B.13-B.16).

Results of the analysis of ranked data are presented in the ANOVA Tables B.13-B.16 in Appendix B. Subject was a significant source for all acoustical measures except for the amplitude of F2 for the second chew. Additionally, the size x subject and food x subject interactions were significant. Furthermore, the food x size x subject interaction was significant for most of the measures except for the amplitude display parameters for the first chew and for amplitudes of F2, F4, and F5 for the second chew. In general, results indicate that the effect of sample diameter was inconsistent and depended on the subject producing the sounds and on the type of food. Significant interactions involving subject were expected because of the type of variability in the acoustical measures. Not only was the intrasubject variability inconsistent, but it frequently was greater than the intersubject variability.

To interpret results of the analysis, results are reported on the original scales of measurement (Sokal and Rohlf, 1969; Sanders, 1990). Interaction means for the measure are presented in Tables C.2-C.10 in Appendix C. Means and the variances then were plotted for the significant interactions to determine if trends occurred for the subjects in the effect of sample diameter on the acoustical measures. Variances were plotted in addition to the means because of the inconsistent intrasubject variability in the acoustical measures (Sanders, 1990). Significant two-way interactions were plotted only for those measures for which the three-way interaction was nonsignificant. Additionally, means and variances were not plotted for all of the acoustical measures. To identify trends in the results, amplitude display parameters were plotted to examine the effect of sample diameter on the duration and amplitude of

mastication sounds. Results for formant frequencies and amplitudes also were plotted to examine the effect of sample diameter on spectral characteristics of the sounds. However, only results for the first 3 formants were plotted because these are the formants which are most often examined for vowel sounds (Denes and Pinson, 1963; Perkins and Kent, 1986).

Amplitude display parameters

Plots of the amplitude display parameters for the first chew of the food samples are presented in Figures IV.19-IV.26. For each measure, plots of the means precede those of the variances. In general, results indicate that the effect of sample diameter on the measures was inconsistent and depended on the subject producing the sounds. For measures of peak amplitude and average amplitude (Figure IV.20 and IV.22), plots of the variances indicate large variations for sounds produced by subject 3. This trend occurred, in particular, for food samples that were 1.27 cm in diameter. In comparison, plots of the variances for measures of duration (Figure IV.24) indicate large variations for sounds produced by subjects 3 and 6. This trend occurred for samples that were 1.90 and 2.54 cm in diameter.

Results also indicate that type of food affected the peak amplitude and average amplitude of sounds of the first chew; however, the effect was inconsistent and depended on the subject producing the sounds (Figures IV.25 and IV.26). For peak amplitude, plots of the variances (Figure IV.26) indicate variation was greater for the carrot samples than for the teething toast samples. This trend occurred for all of the subjects except subject 6. For average amplitude (Figure IV.26), no trend occurred for the 6 subjects in the effect of food type on the variances of this measure.

Plots of the amplitude display parameters for the second chew of the food samples are presented in Figures IV.27-IV.32. Results indicate that for all measures the effect of sample diameter was inconsistent and depended on the type of food and on the subject producing the sounds.

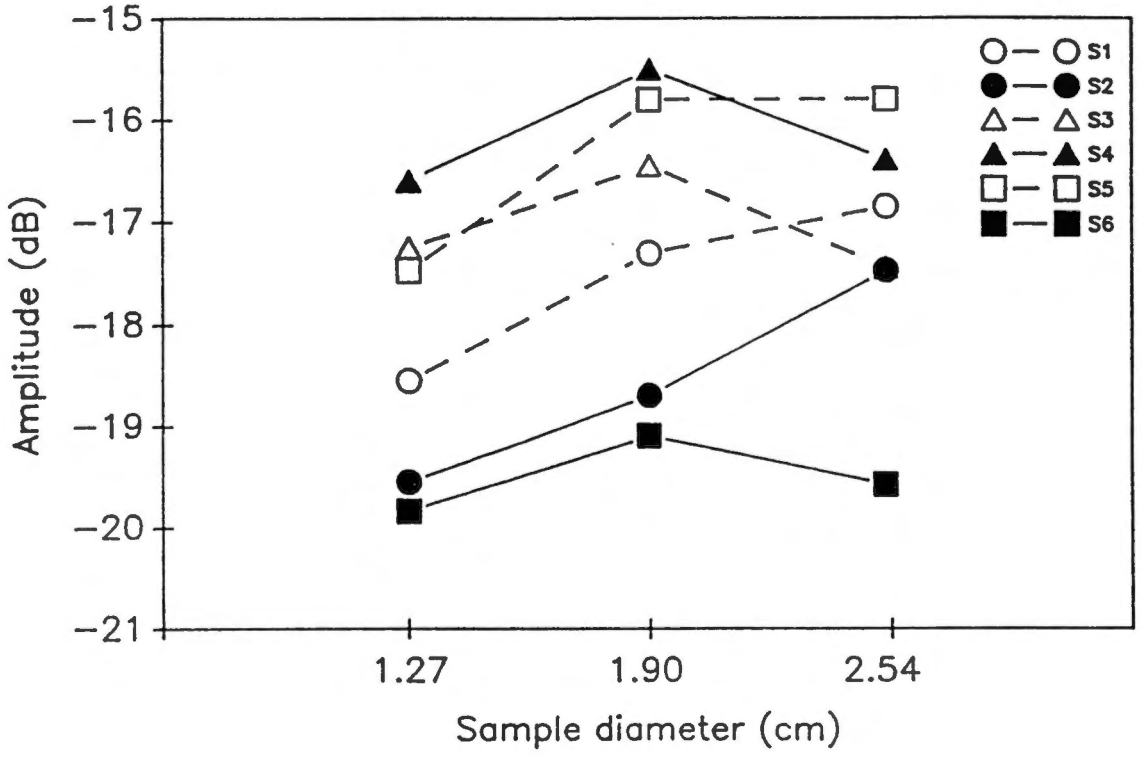


Figure IV.19 – Peak amplitude of sounds for the first chew as a function of subject (S1-S6) x sample diameter irrespective of food type (n=20 repetitions). Amplitude was measured relative to the full scale output of the sound spectrograph.

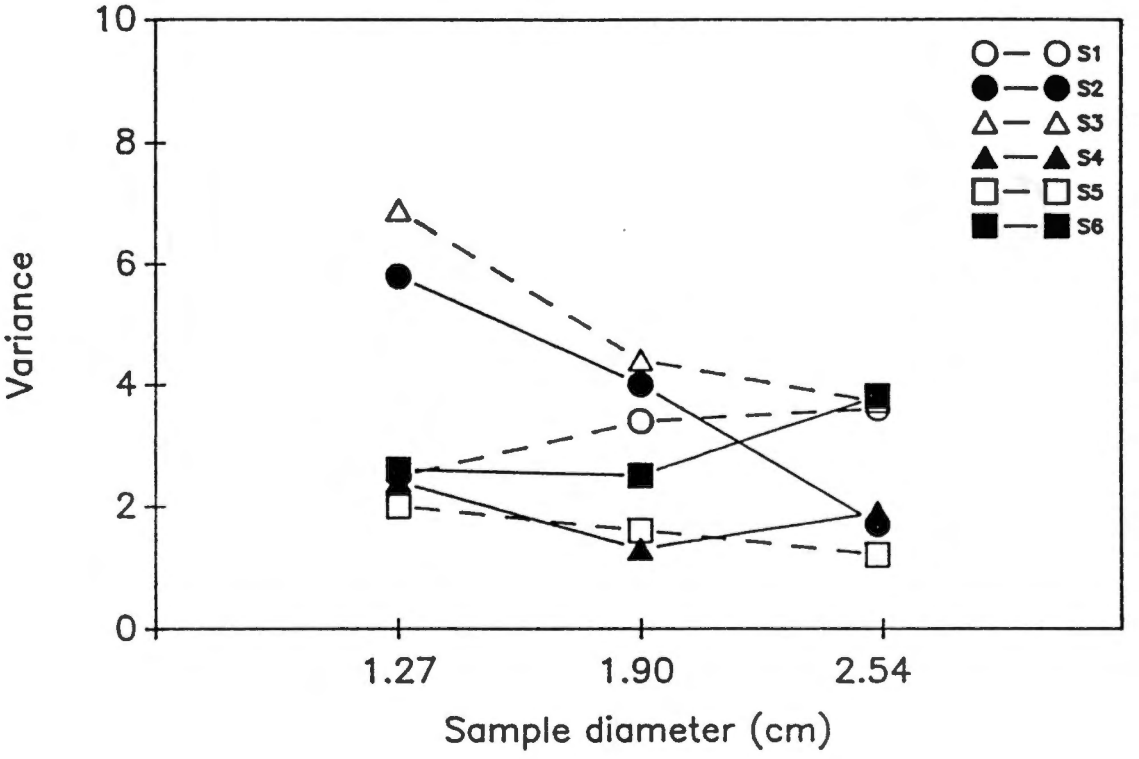


Figure IV.20 – Variance of peak amplitude of sounds for the first chew as a function of subject (S1-S6) x sample diameter irrespective of food type (n=20 repetitions).

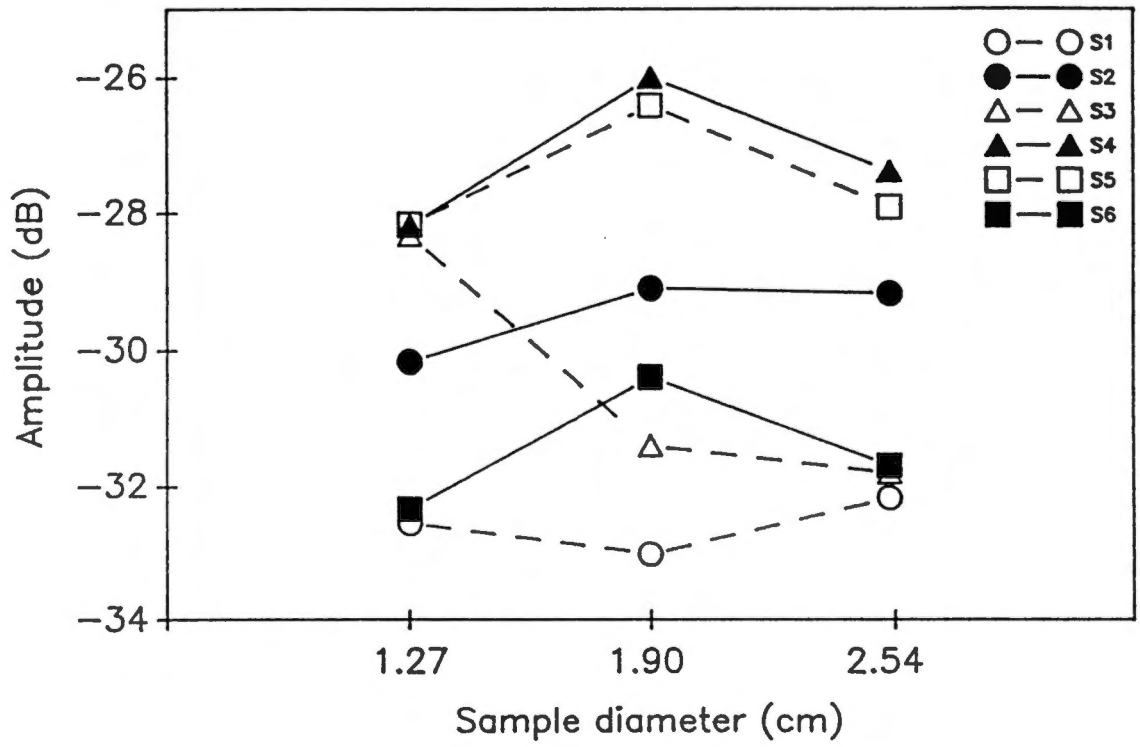


Figure IV.21 – Average amplitude of sounds for the first chew as a function of subject (S1-S6) x sample diameter irrespective of food type (n=20 repetitions). Amplitude was measured relative to the full scale output of the sound spectrograph.

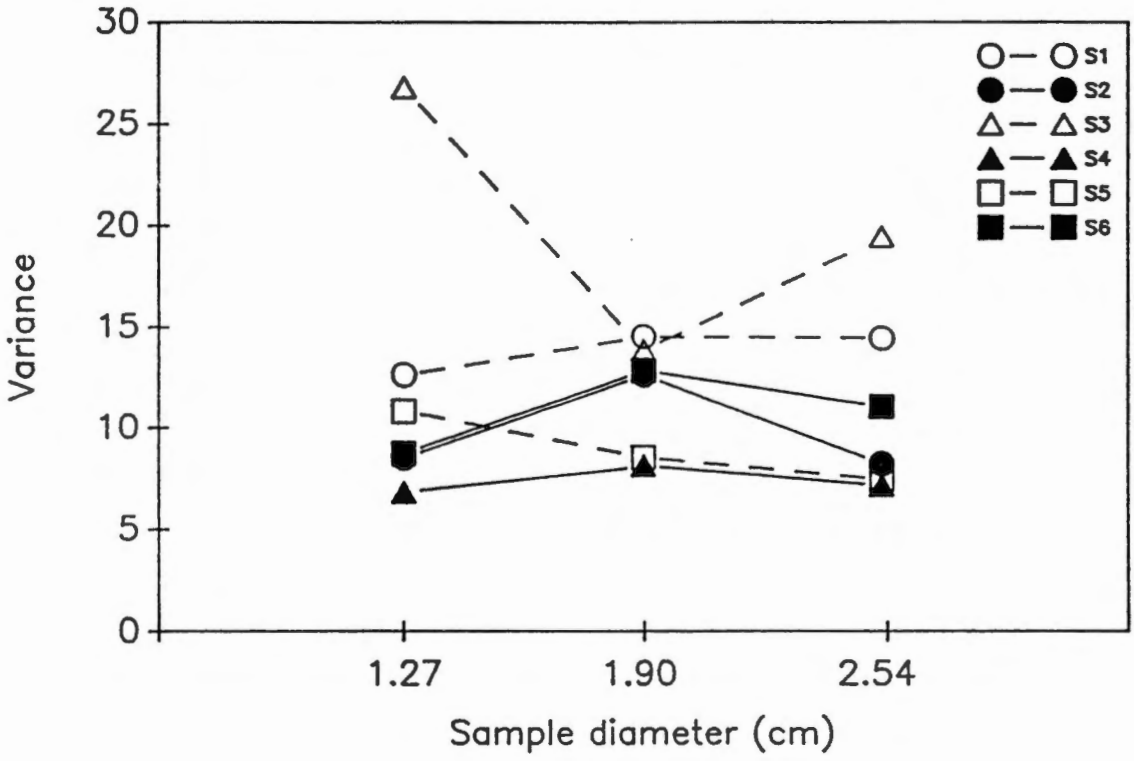


Figure IV.22 – Variance of average amplitude of sounds for the first chew as a function of subject (S1-S6) x sample diameter irrespective of food type (n=20 repetitions).

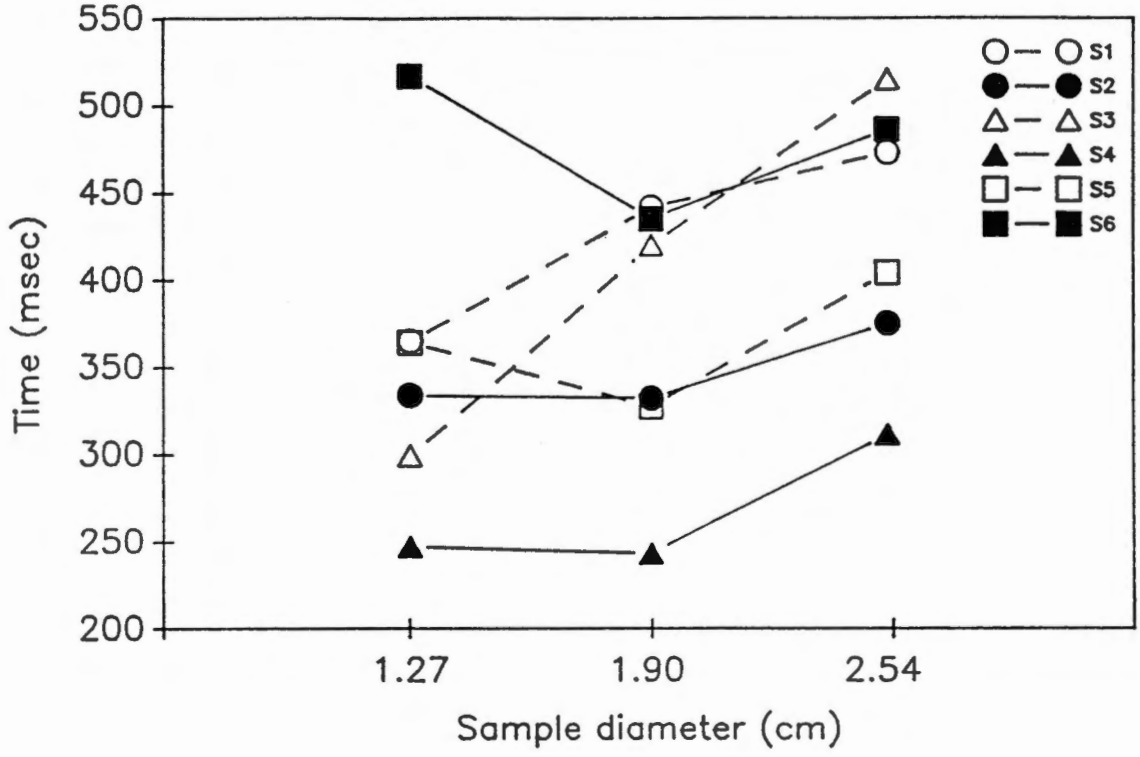


Figure IV.23 – Duration of sounds for the first chew as a function of subject (S1-S6) x sample diameter irrespective of food type (n=20 repetitions).

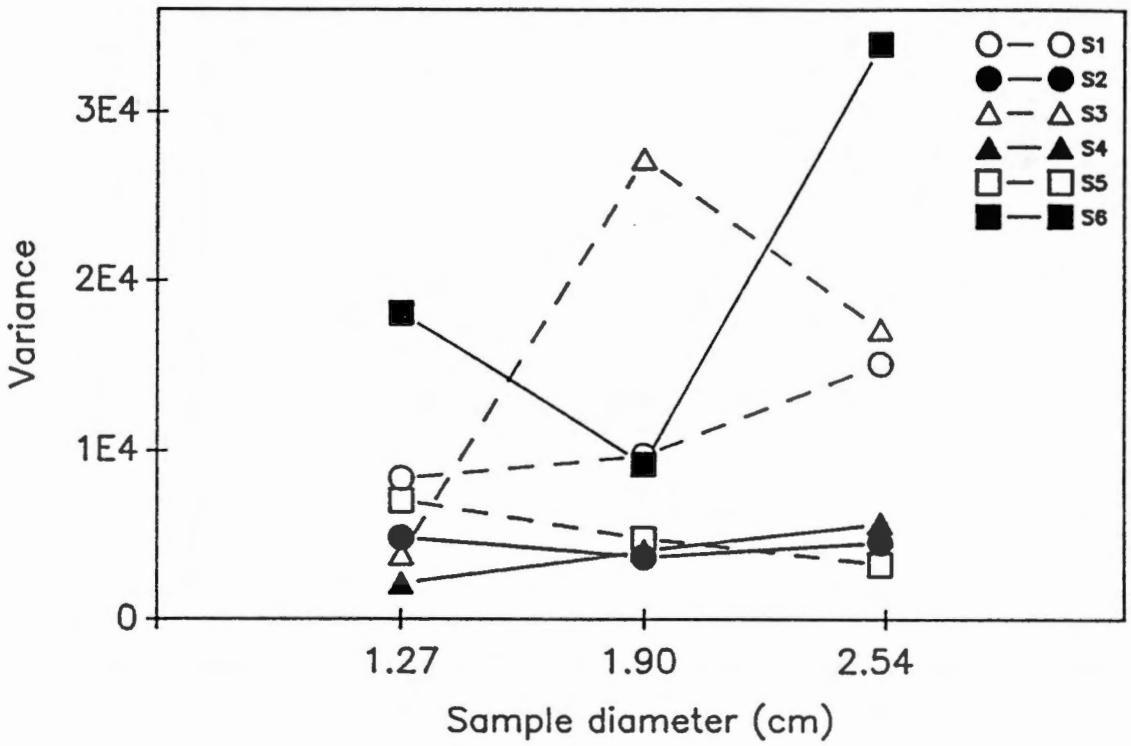


Figure IV.24 – Variance of duration of sounds for the first chew as a function of subject (S1-S6) x sample diameter irrespective of food type (n=20 repetitions).

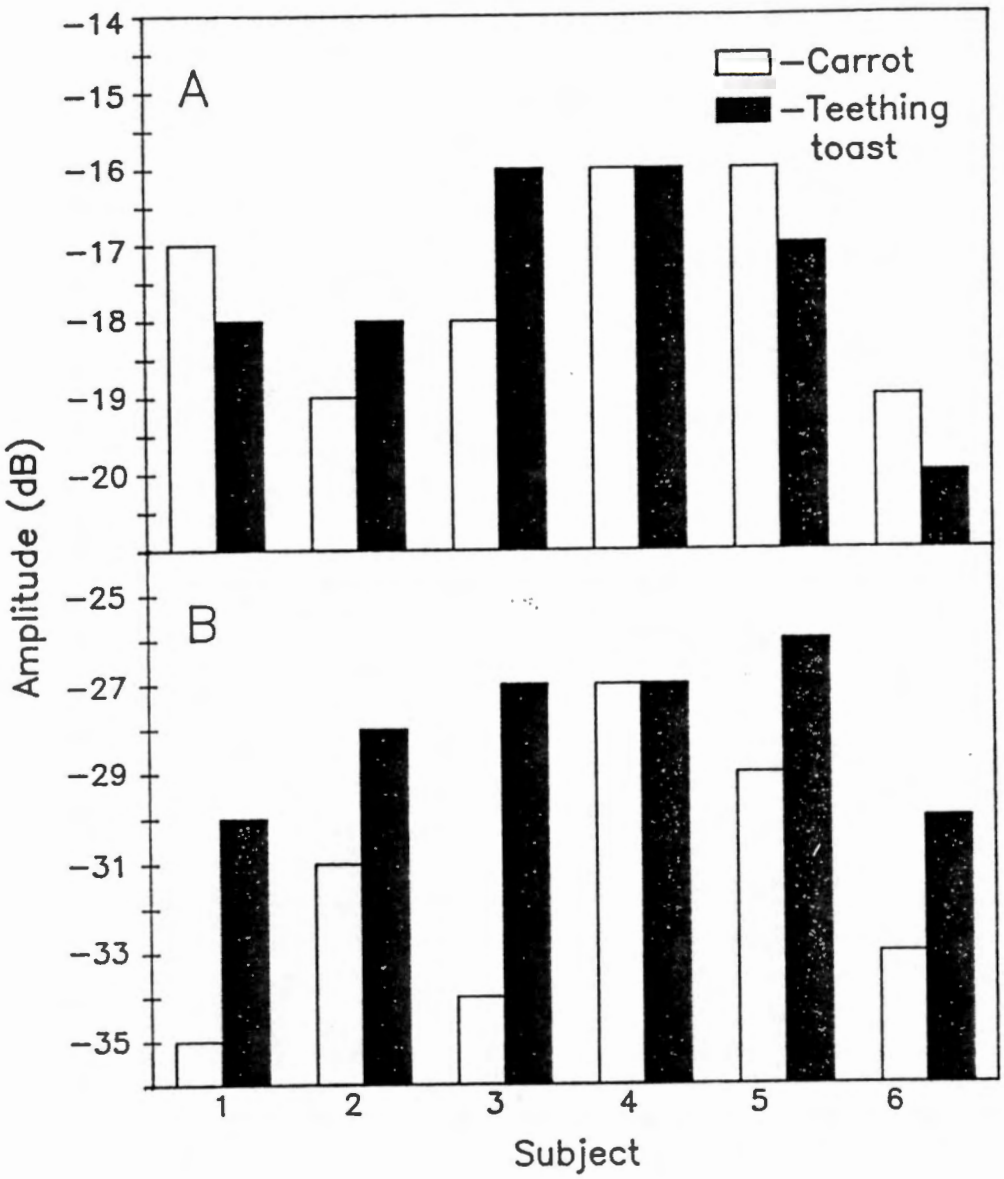


Figure IV.25 – Peak amplitude (A) and average amplitude (B) of sounds for the first chew as a function of food x subject (S1-S6) irrespective of sample diameter (n=30 repetitions). Amplitude was measured relative to the full scale output of the sound spectrograph.

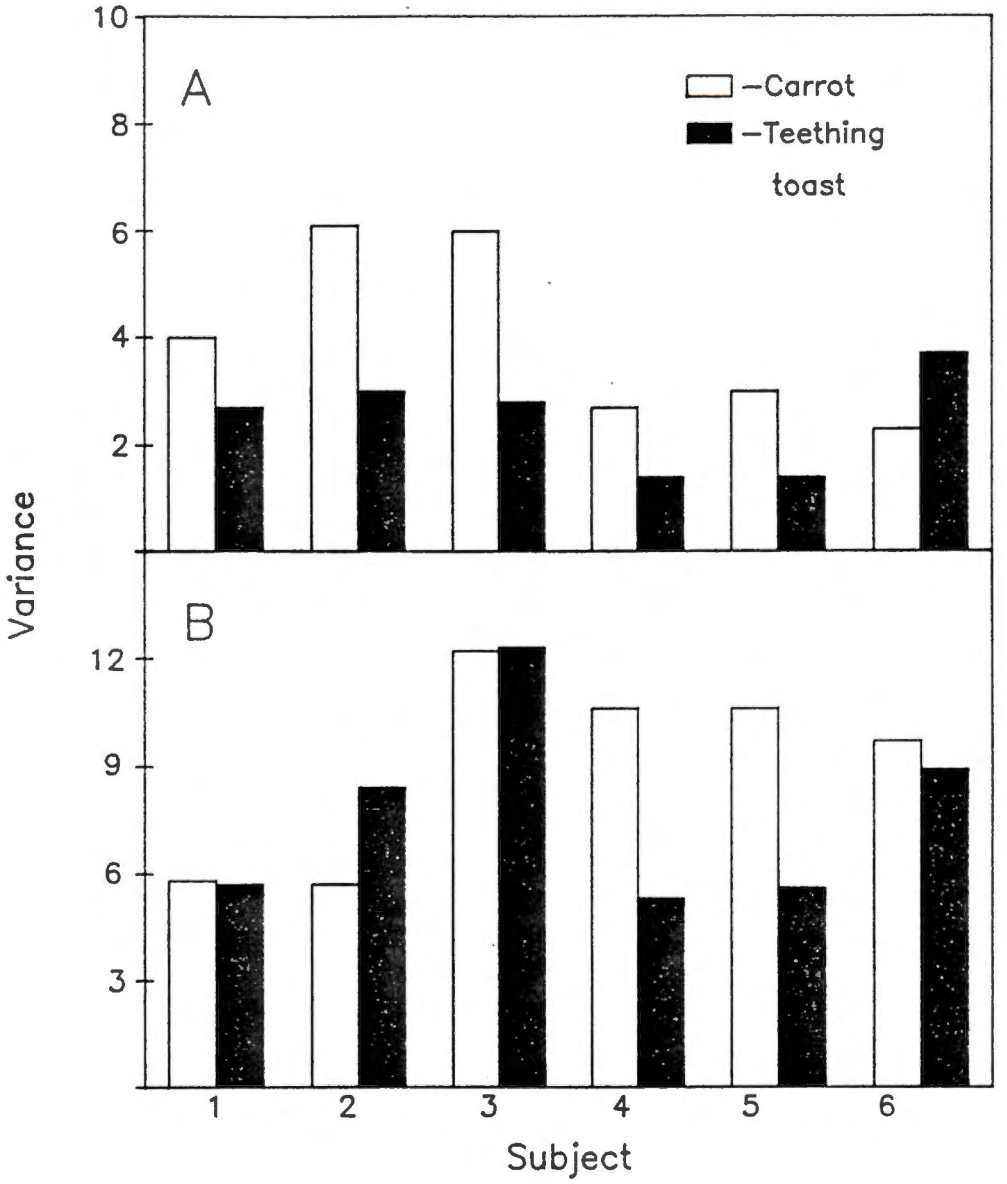


Figure IV.26 – Variance of peak amplitude (A) and average amplitude (B) of sounds for the first chew as a function of food x subject (S1-S6) irrespective of sample diameter (n=30 repetitions).

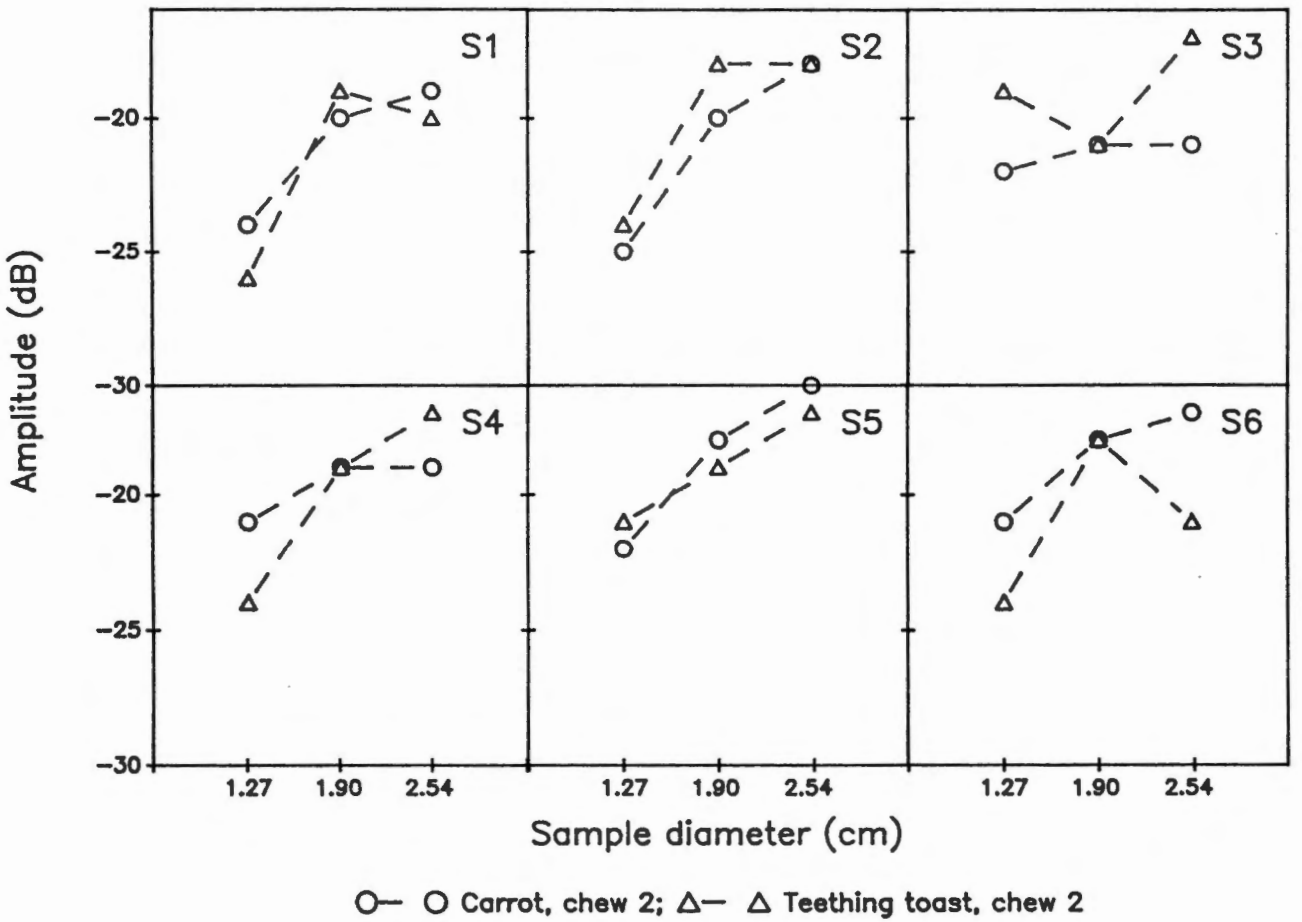


Figure IV.27 – Peak amplitude of sounds for the second chew as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions). Amplitude was measured relative to the full scale output of the sound spectrograph.

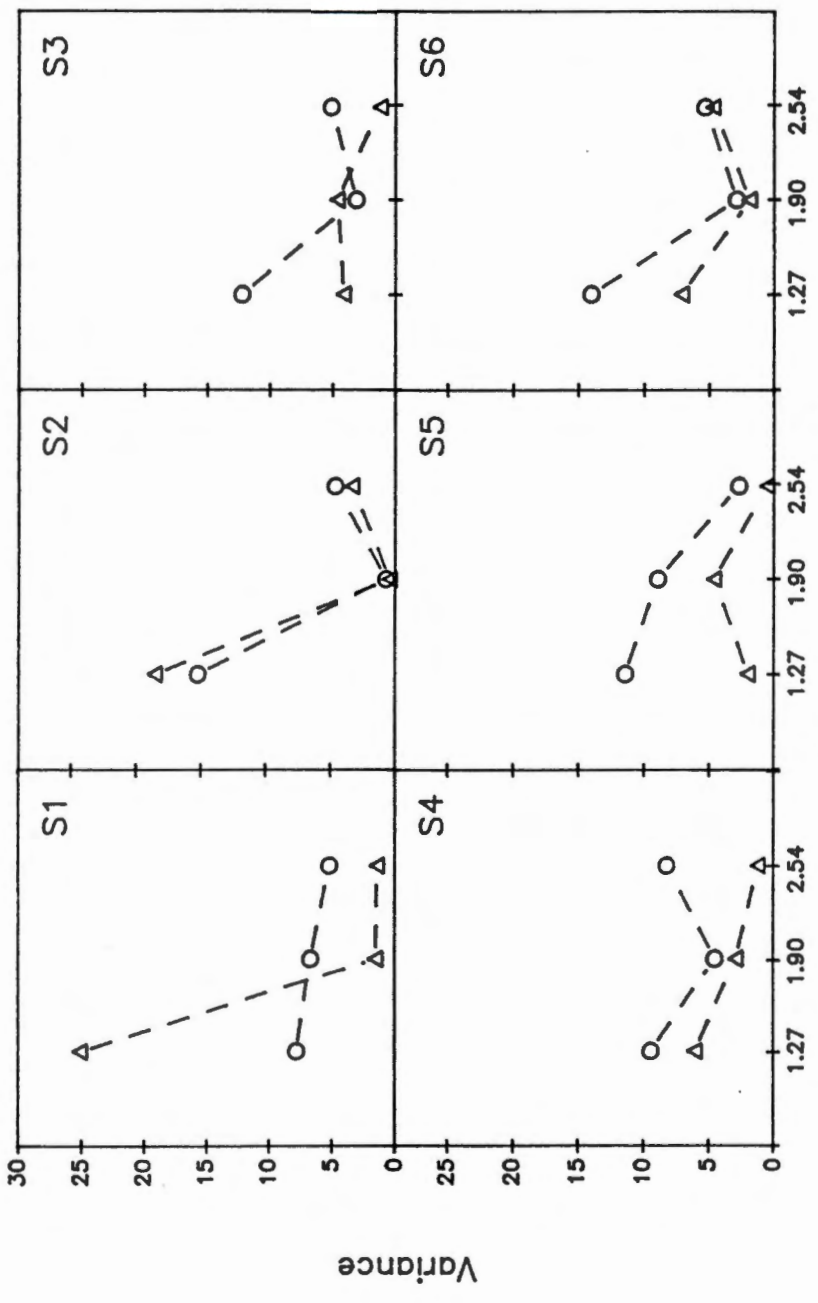


Figure IV.28 - Variance of the peak amplitude of sounds for the second chew as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions).

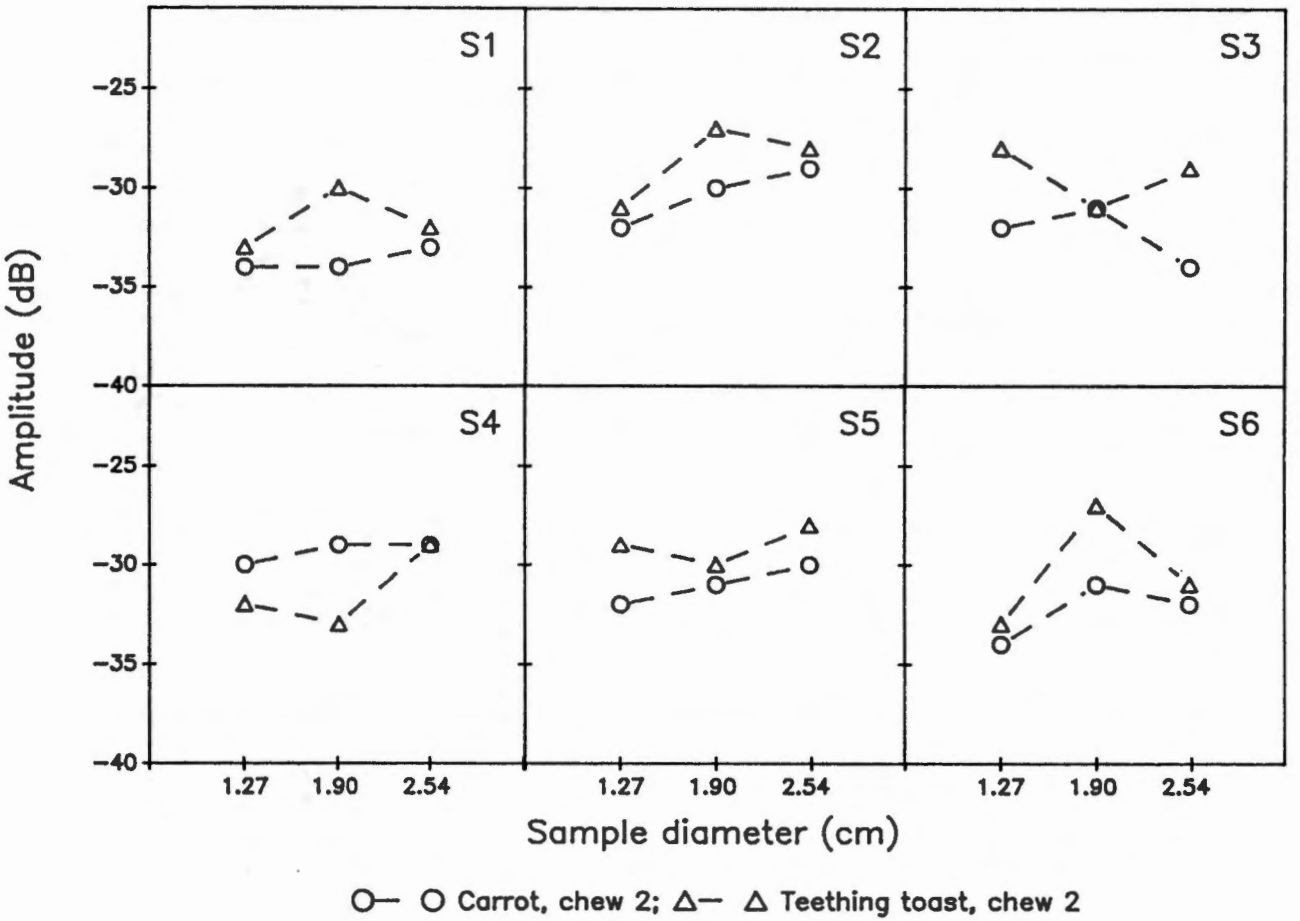


Figure IV.29 – Average amplitude of sounds for the second chew as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions). Amplitude was measured relative to the full scale output of the sound spectrograph.

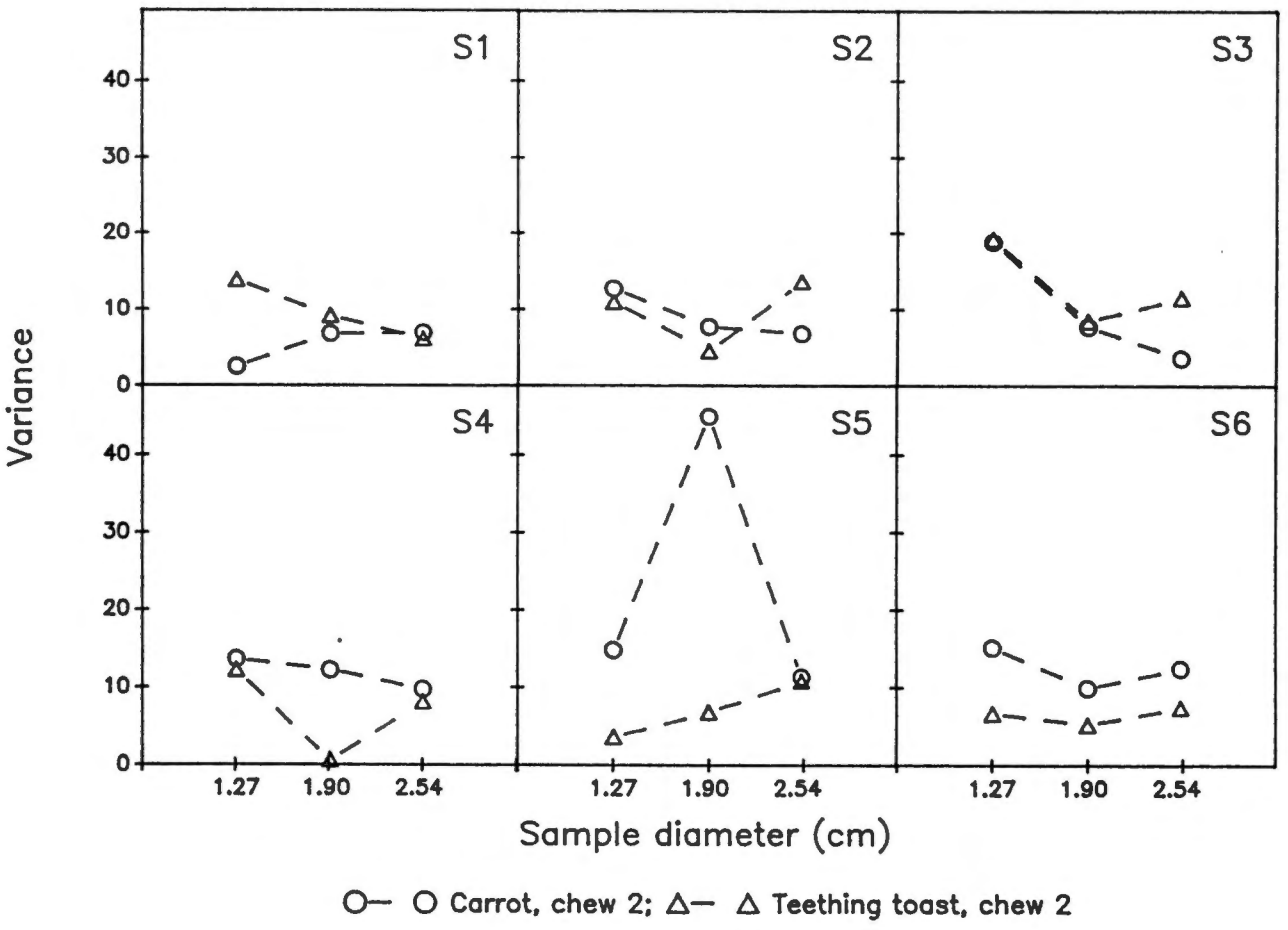


Figure IV.30 – Variance of the average amplitude of sounds for the second chew as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions).

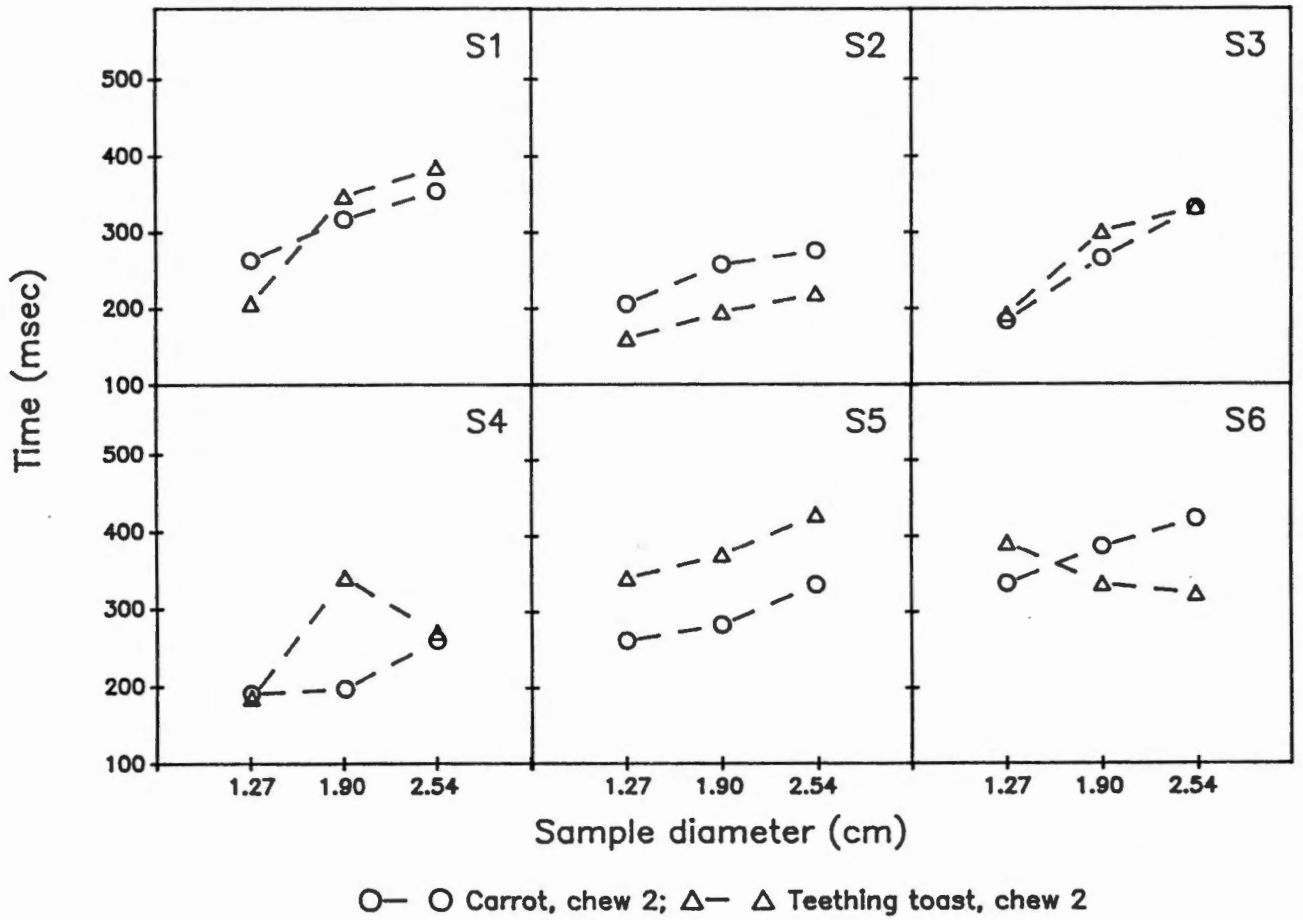


Figure IV.31 – Duration of sounds for the second chew as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions).

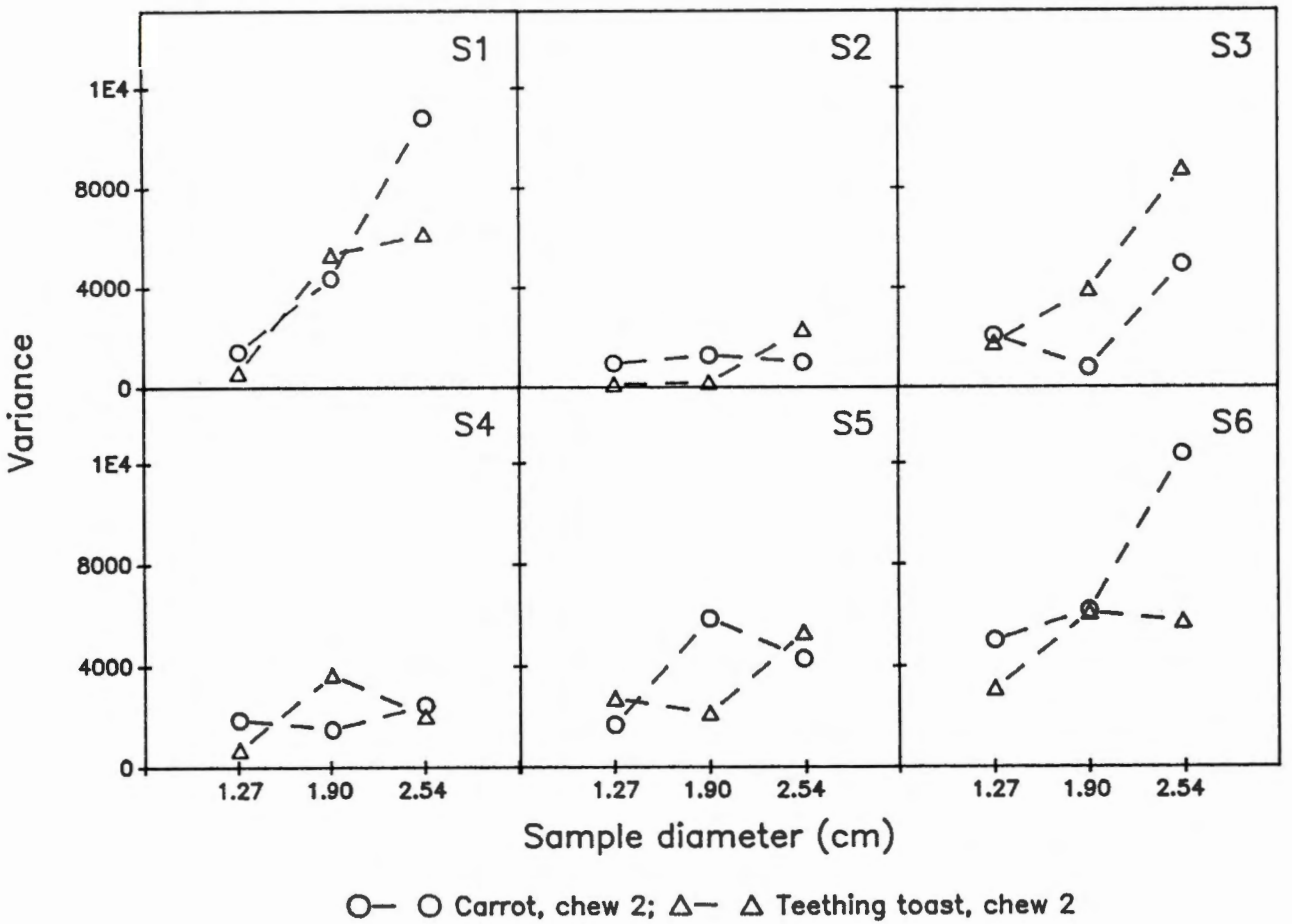


Figure IV.32 – Variance of the duration of sounds for the second chew as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions).

For peak amplitude, plots of the variances (Figure IV.28) indicate that variation in this measure was greater for the 1.27-cm samples than for the 1.90- and 2.54-cm samples. This trend occurred particularly for the carrot samples and for sounds produced by all of the subjects except subject 4. Plots of the variances for average amplitude (Figure IV.30) indicate that the variation in this measure was largest for the sounds produced by subject 5. For this subject, the variation was large for the 1.90-cm carrot samples. In comparison, variations in measures of duration (Figure IV.32) were large for sounds produced by subjects 1, 3, and 6. This trend occurred for the 2.54-cm samples of both types of food.

Formant amplitudes

Results of the analysis of the amplitudes of formants 1 and 3 indicate that the effect of sample diameter on the measures was inconsistent and depended on the type of food and on the subject producing the sounds. This effect occurred for measures of both chews. Plots of the means and variances of the measures are presented in Figures IV.33-IV.36. Results for both chews are presented in the same figure.

For the amplitude of the first formant of the first chew (Figure IV.34), no trend occurred for the variation in this measure. For the second chew, variations in measures of amplitude were greater for the carrot samples than for the teething toast samples. This trend occurred for sounds produced by subjects 2, 3, 4, and 5.

For the third formant (Figure IV.36), variation was large for sounds produced by subject 1. For this subject, variations were large for sounds of the 1.27 and 2.54-cm carrot samples. For the second chew, variations were large for sounds produced by subjects 2 and 5. This trend occurred for the 2.54-cm carrot samples.

Plots of the amplitude of the second formant are presented in Figures IV.37-IV.40. For the first chew, the size x food x subject interaction was a significant source of variation. Plots of the variances (Figure IV.38) indicate a trend related to the diameter of the sample and the type of food. For the carrot sample, variation

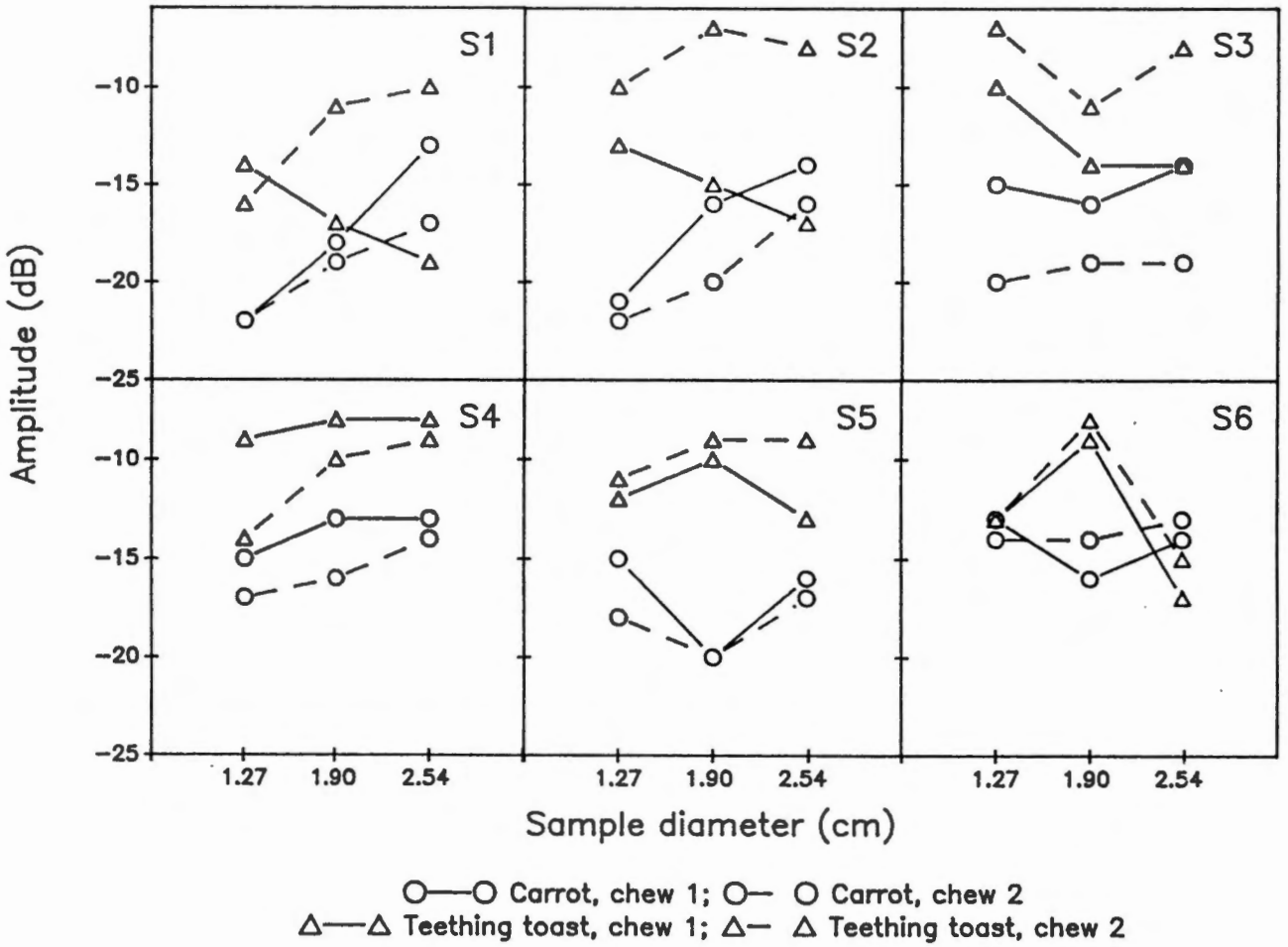


Figure IV.33 – Amplitude of the first formant of sounds for the first and second chews as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions). Amplitude was measured relative to a calibration tone (1000 Hz, 80 dB).

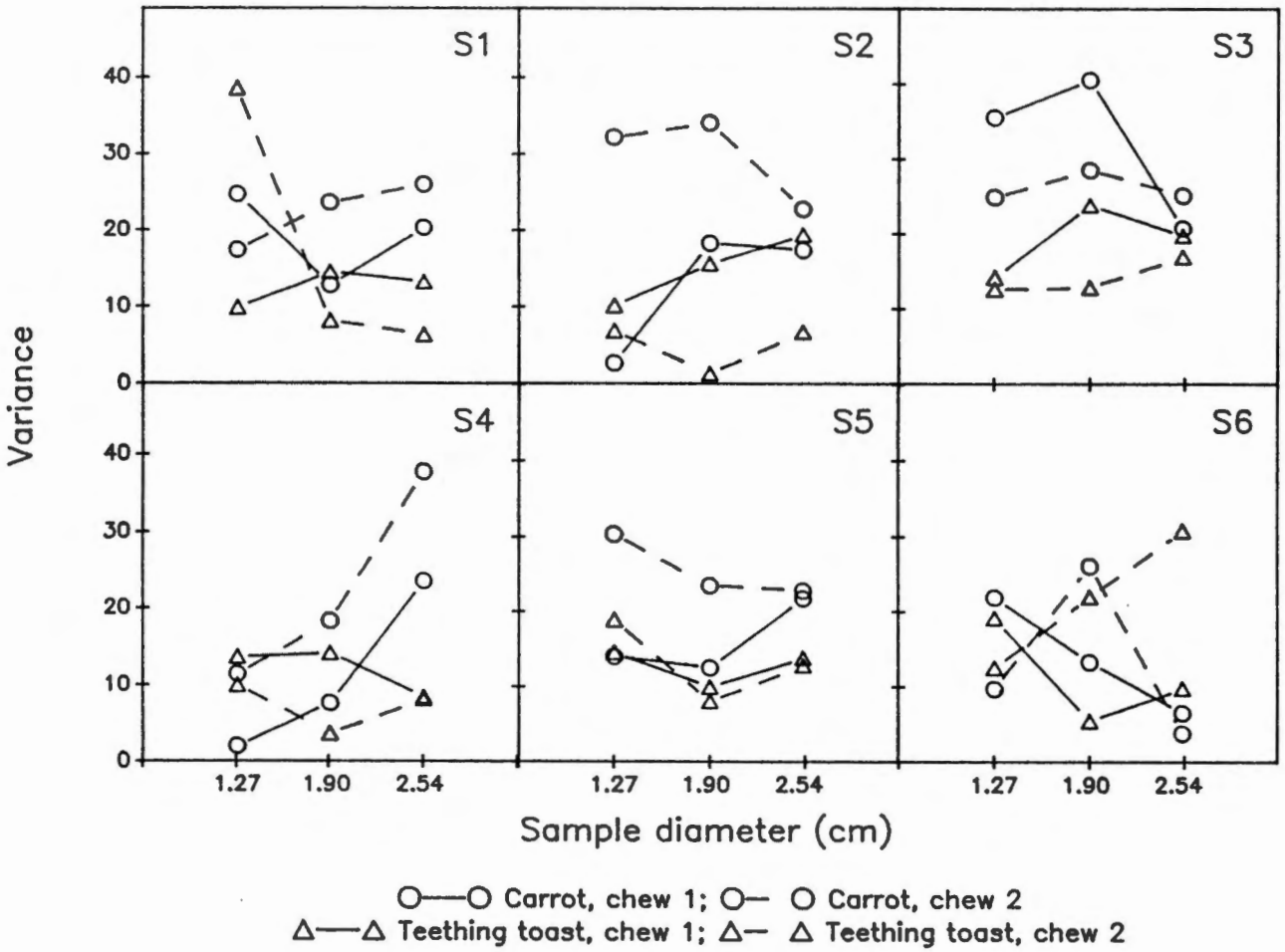


Figure IV.34 – Variance of the amplitude of the first formant of sounds for the first and second chews as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions).

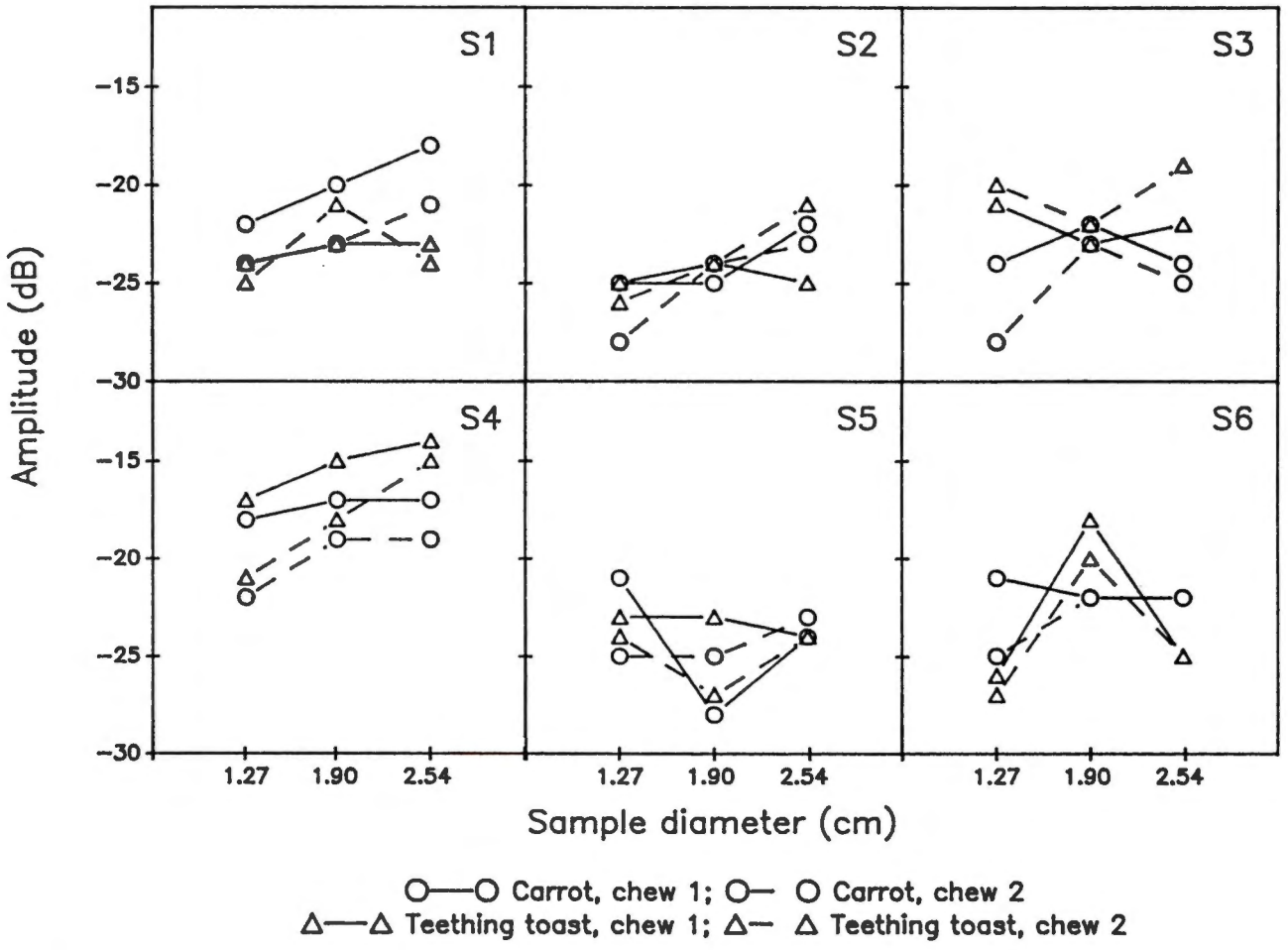


Figure IV.35 – Amplitude of the third formant of sounds for the first and second chews as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions). Amplitude was measured relative to a calibration tone (1000 Hz, 80 dB).

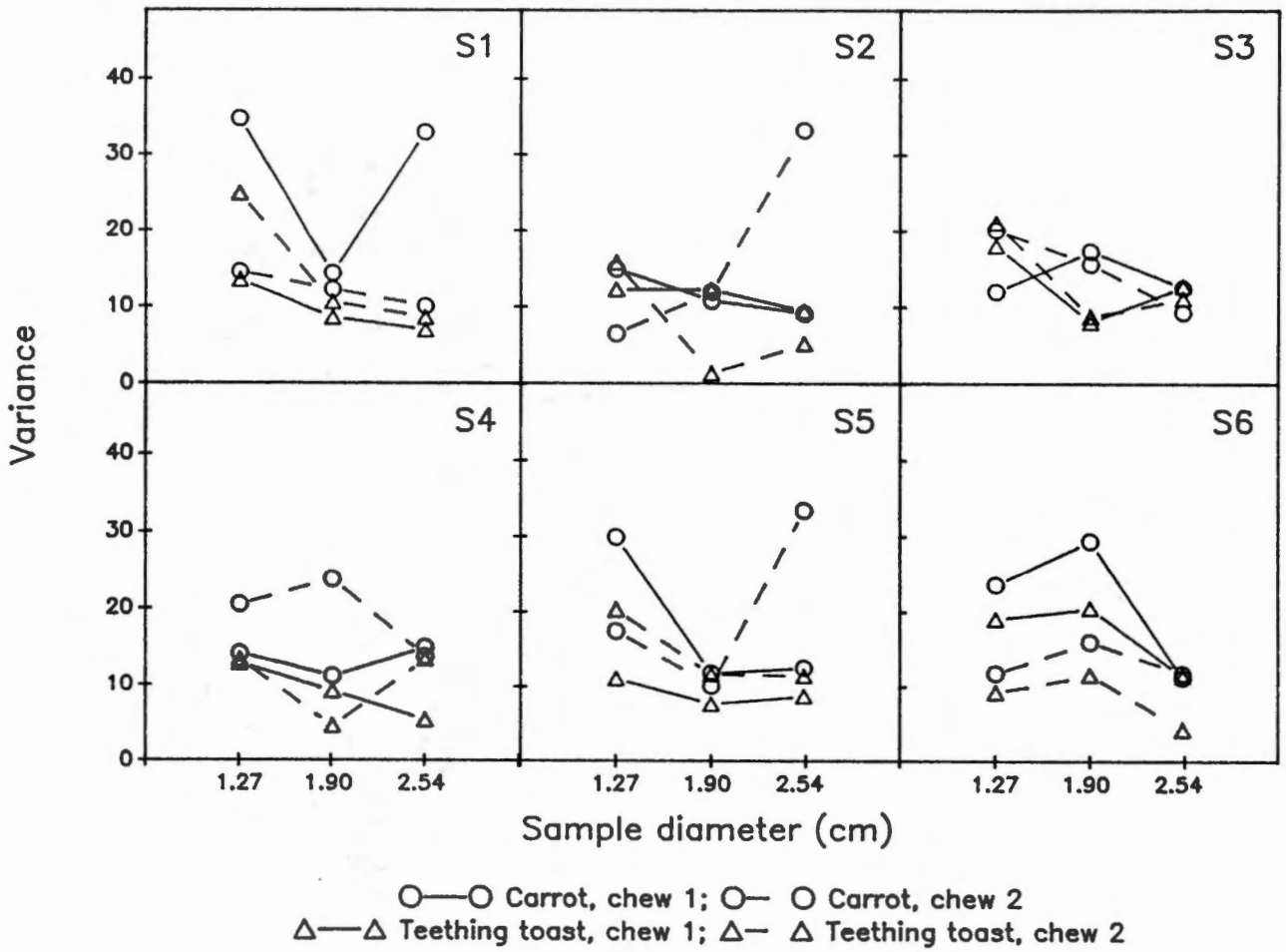


Figure IV.36 – Variance of the amplitude of the third formant of sounds for the first and second chews as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions).

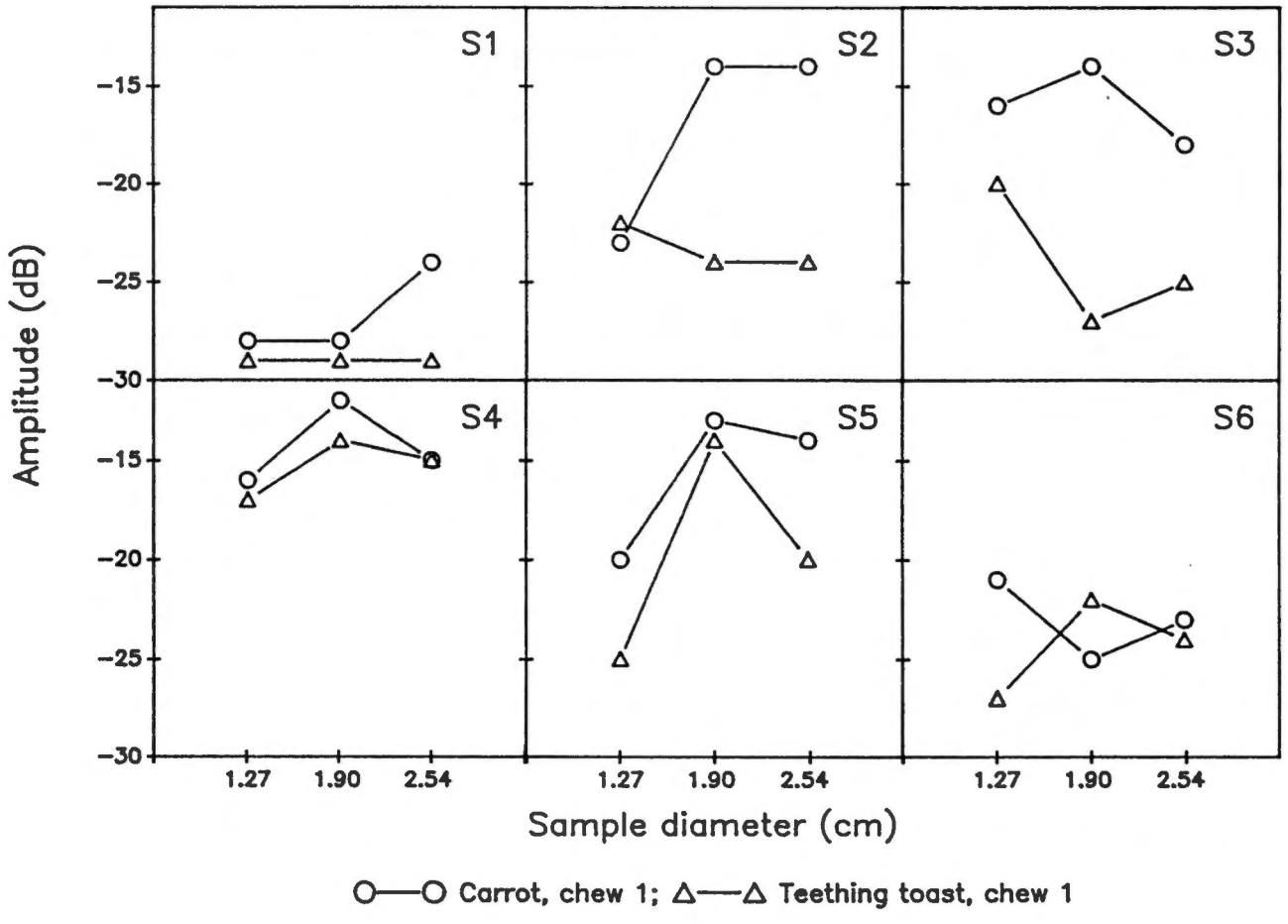


Figure IV.37 – Amplitude of the second formant of sounds for the first chew as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions). Amplitude was measured relative to a calibration tone (1000 Hz, 80 dB).

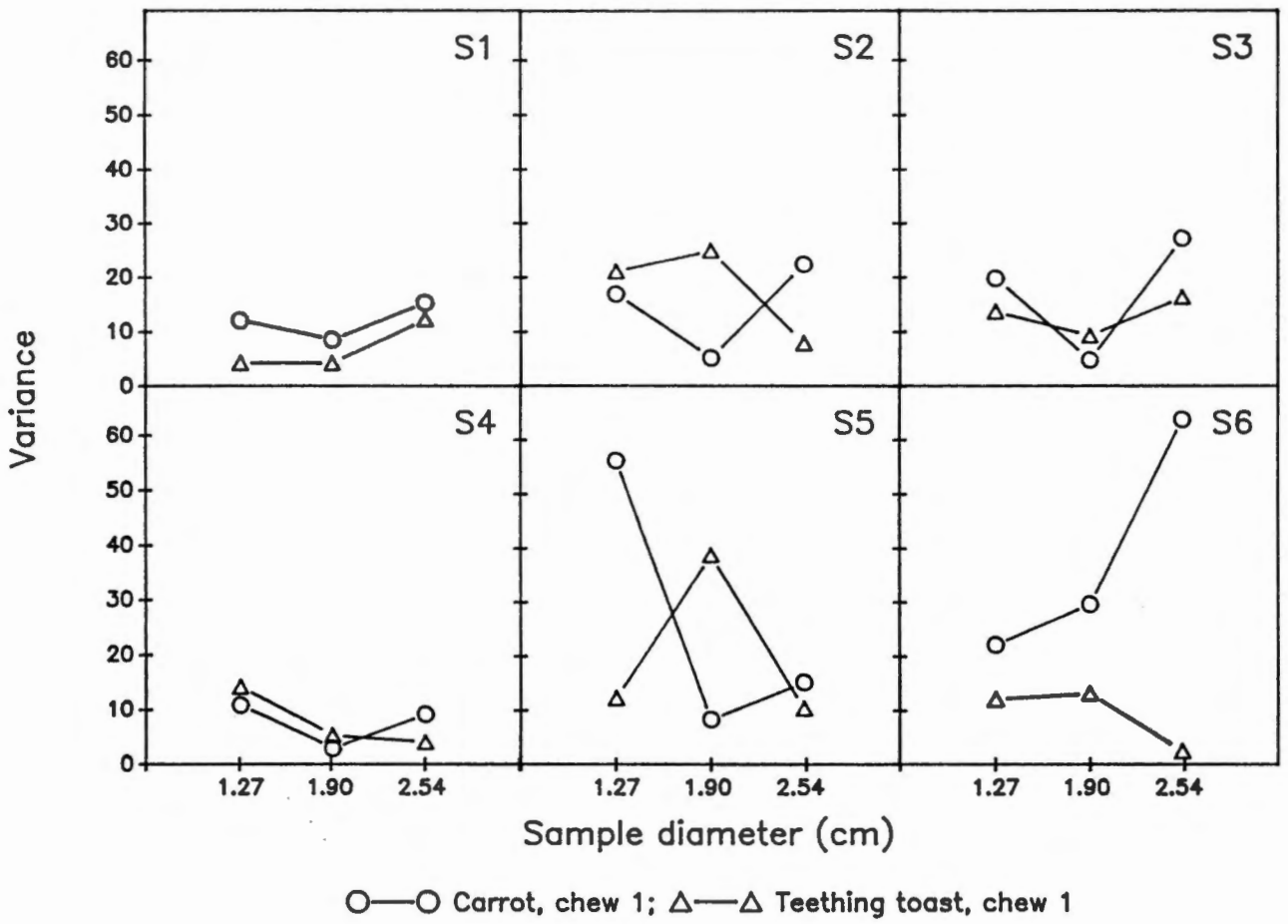


Figure IV.38 – Variance of the amplitude of the second formant of sounds for the first chew as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions).

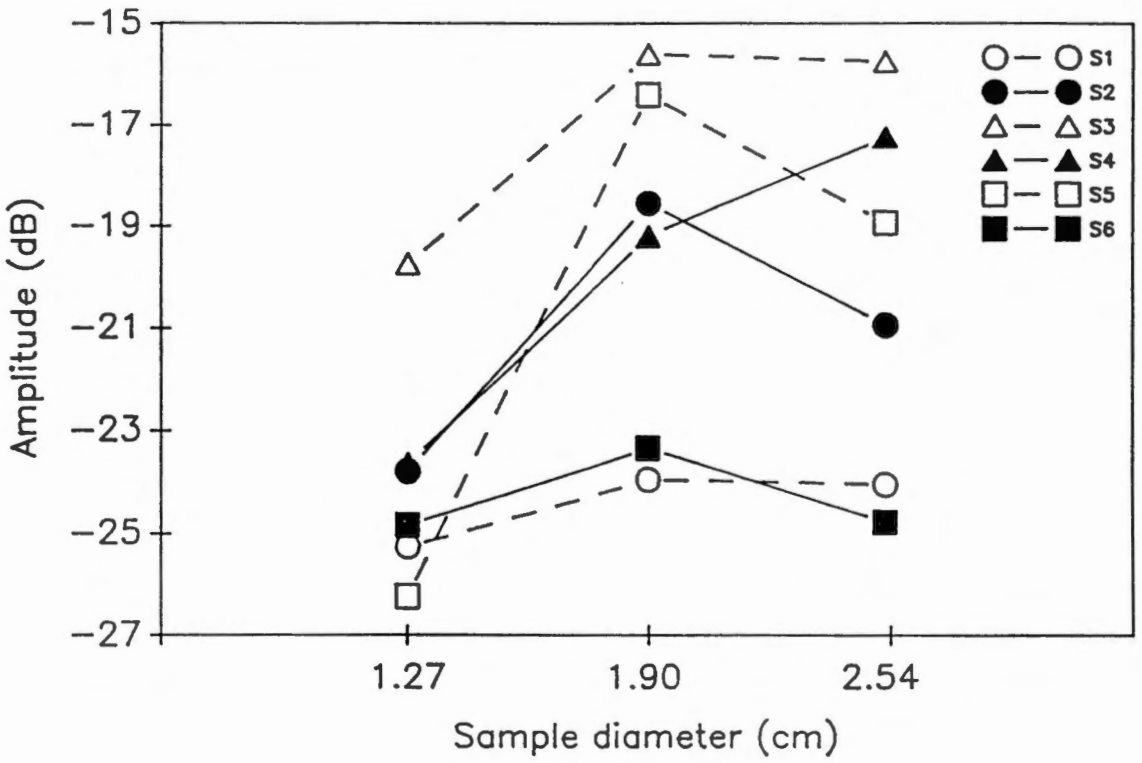


Figure IV.39 – Amplitude of the second formant of sounds for the second chew as a function of subject (S1-S6) x sample diameter irrespective of food type (n=20 repetitions). Amplitude was measured relative to that of a calibration tone (1000 Hz, 80 dB).

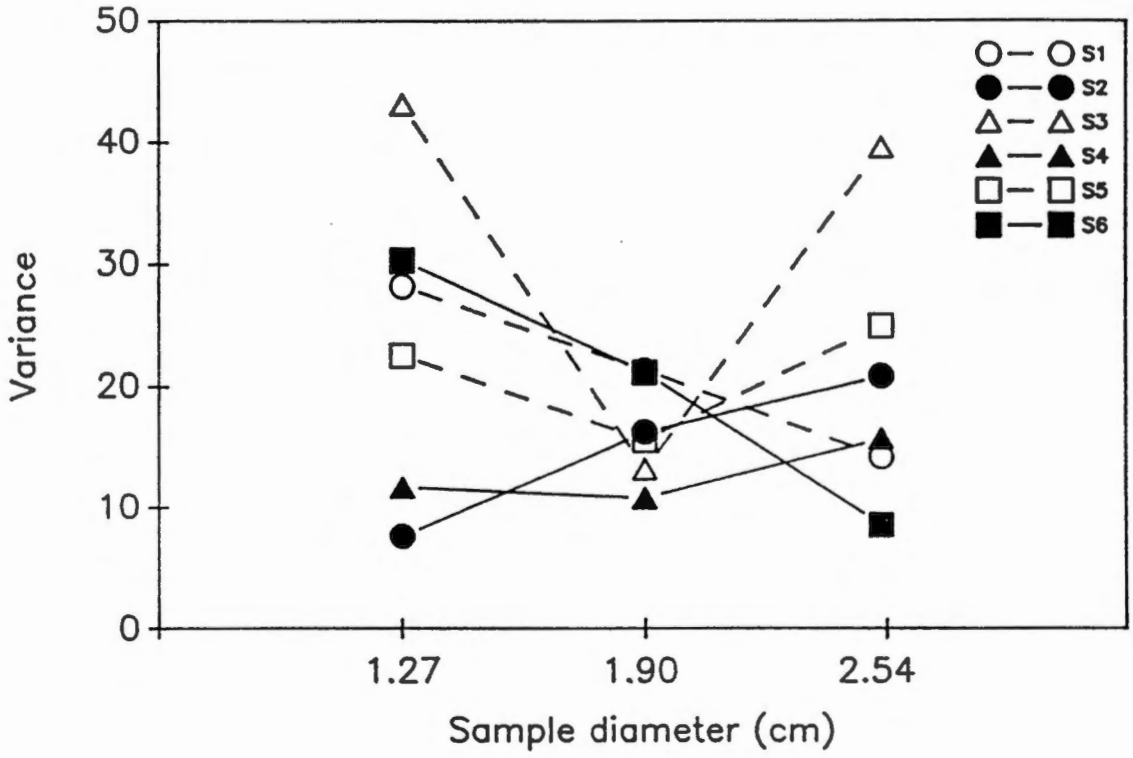


Figure IV.40 – Variance of the amplitude of the second formant of sounds for the second chew as a function of subject (S1-S6) x sample diameter irrespective of food type (n=20 repetitions).

was small for the 1.90-cm samples. This trend occurred for all subjects except subject 6. In contrast, no trend occurred in the variances for the teething toast samples. For the second chew, the size x subject interaction was significant source of variation in measures of amplitude of the second formant. Plots of the variance (Figure IV.40) indicate a trend related to the diameter of the sample. For sounds produced by all 6 subjects, variations in the measure were smaller for the 1.27-cm samples than for the 1.90 and 2.54-cm samples.

Formant frequencies

The size x food x subject interaction was a significant source of variation in measures of frequencies of formants 1-3. Plots of the means and of the variances are presented in Figures IV.41-IV.46. Results for both chews are presented in the same figure.

Plots of the variances for the frequency of the first formant (Figure IV.42) indicate that for both chews variances were large for measures of sounds produced by subjects 2, 3, and 6 for the 1.27-cm carrot samples. Results were similar for the second and third formants. Plots of the variances (Figure IV.44 and IV.46) indicate that for both chews variances were large for measures of sounds produced by subject 3 for the 1.27-cm carrot sample.

Summary

Analysis of ranks of the acoustical measures revealed that the effect of sample diameter on the measures was inconsistent. In most cases, this effect depended on the type of food and on the subject producing the sounds. Additionally, the effect occurred for measures of the first and of the second chews and reflected the inconsistent intrasubject variability in the measures. However, evaluation of plots of the variances of the measures revealed trends related to the type of food, diameter of the food sample, and subject producing the sounds.

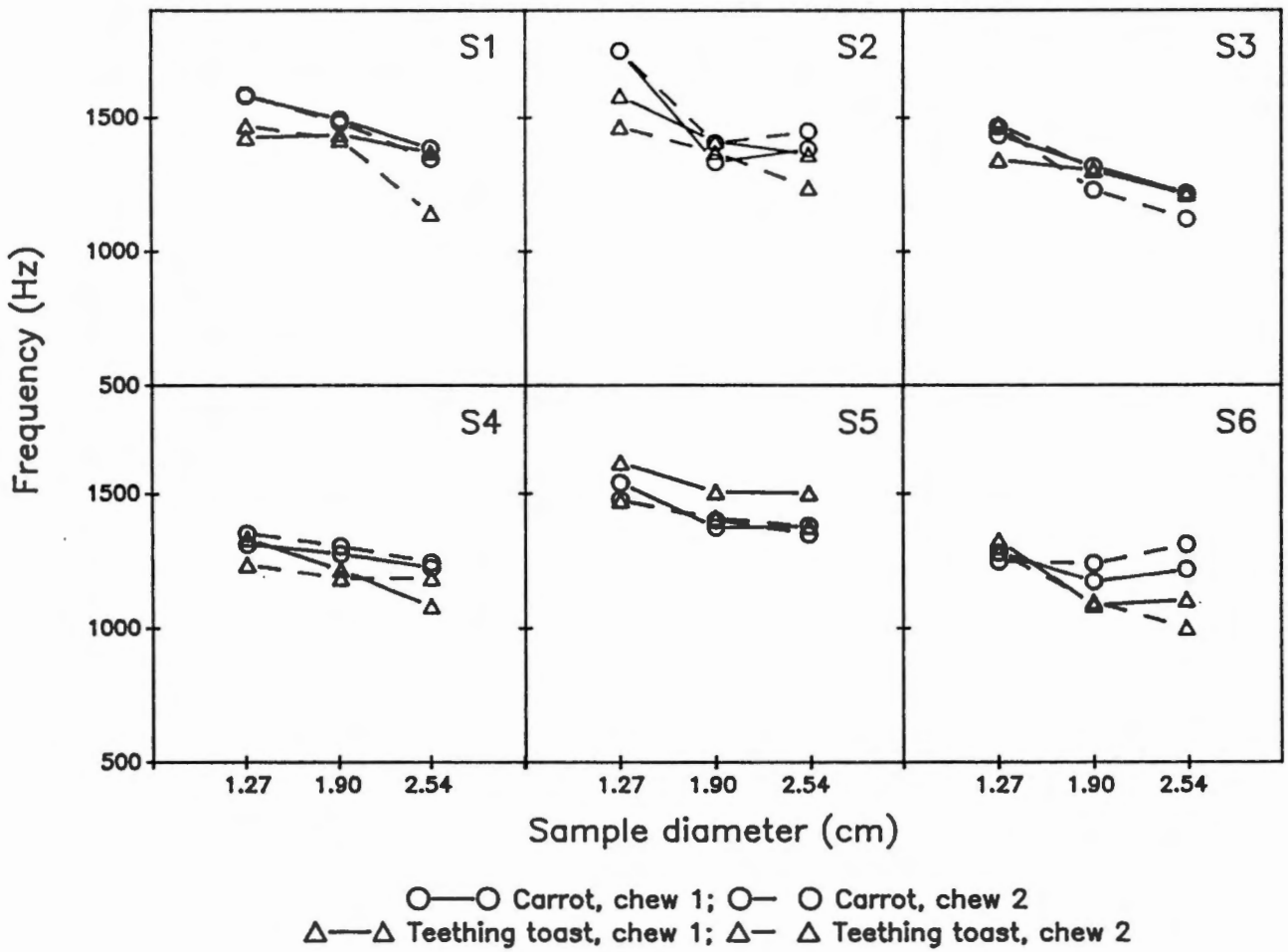


Figure IV.41 – Frequency of the first formant of sounds for the first and second chews as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions).

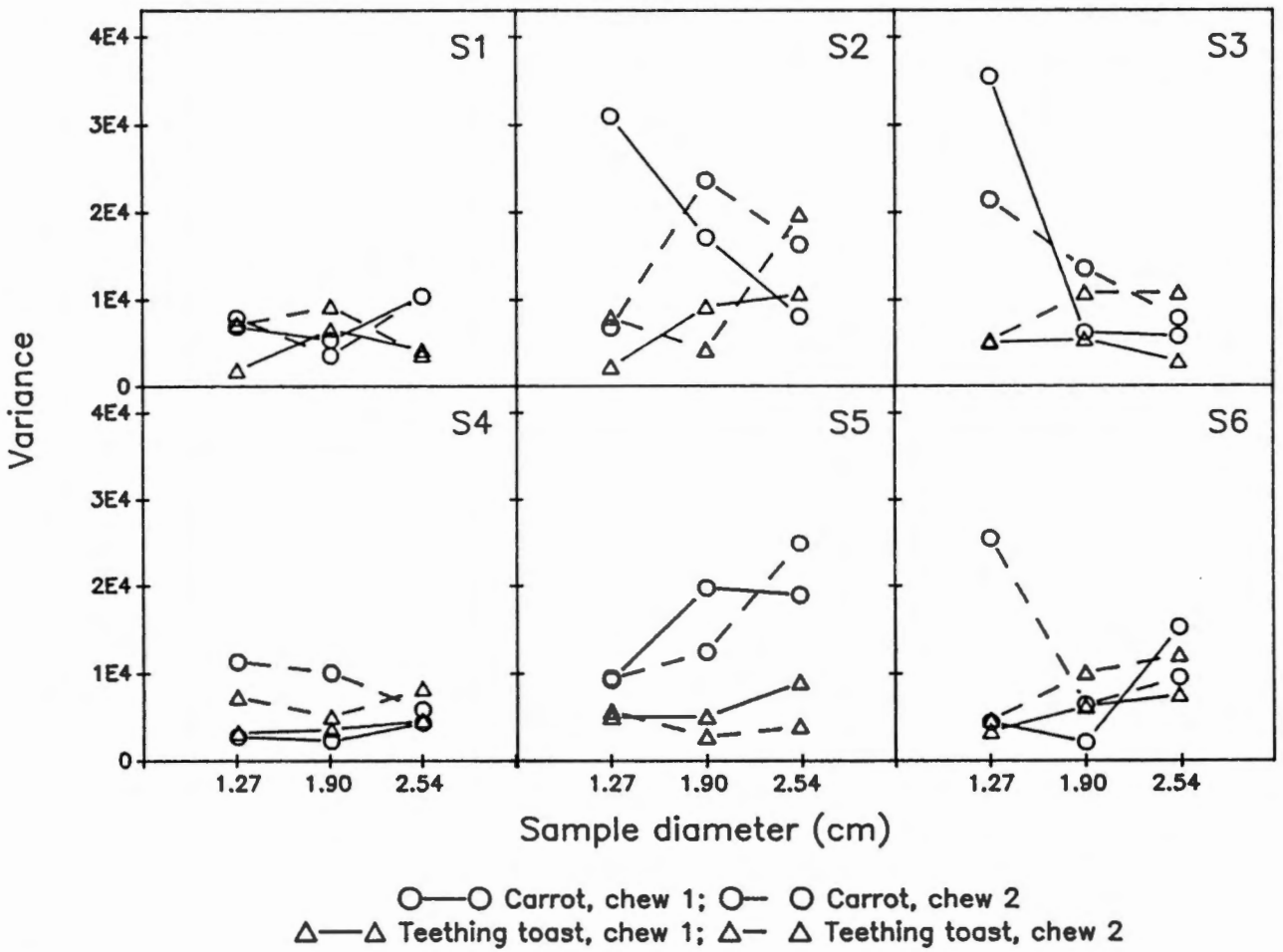


Figure IV.42 – Variance of the frequency of the first formant of sounds for the first and second chews as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions).

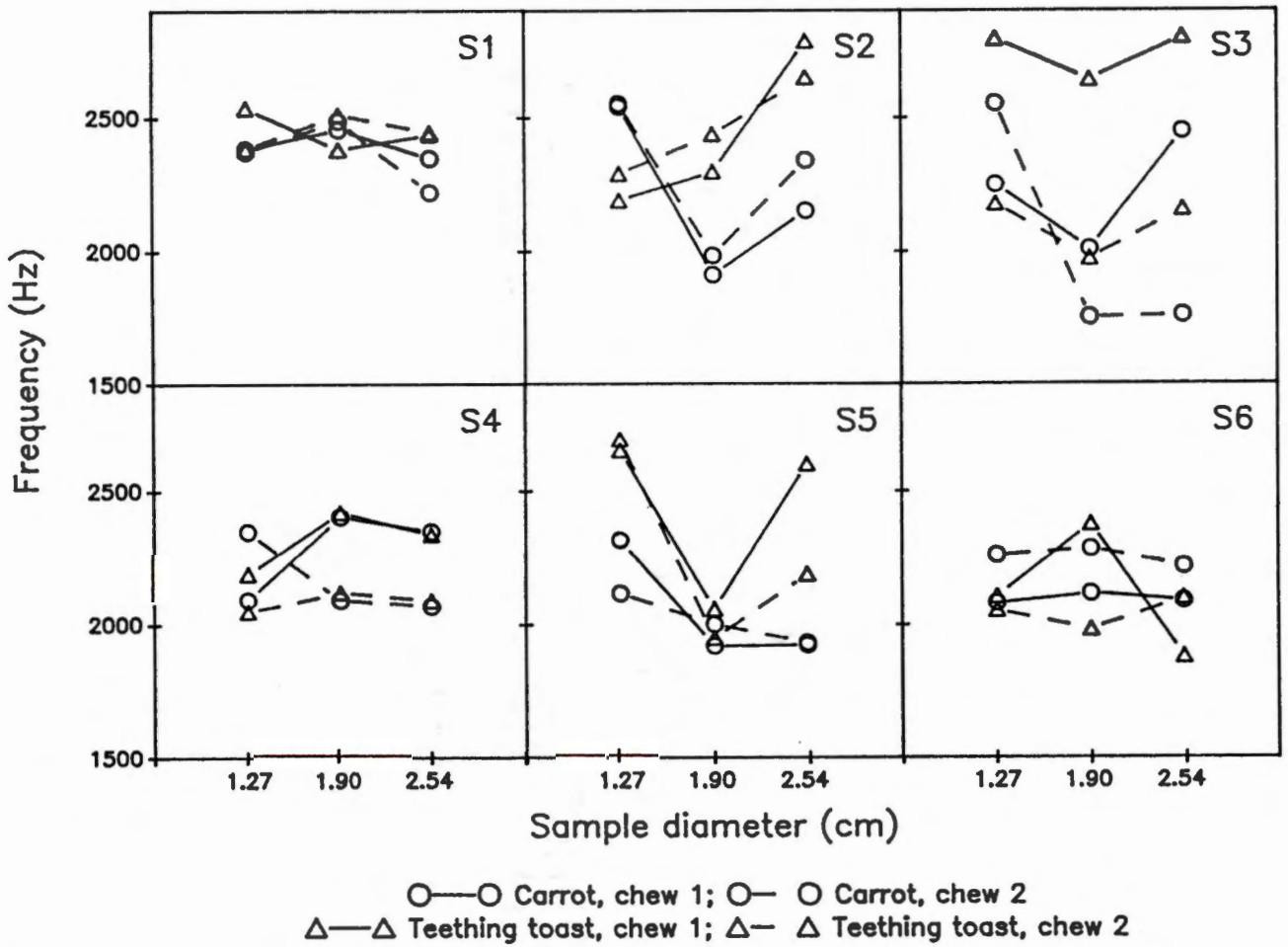


Figure IV.43 – Frequency of the second formant of sounds for the first and second chews as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions).

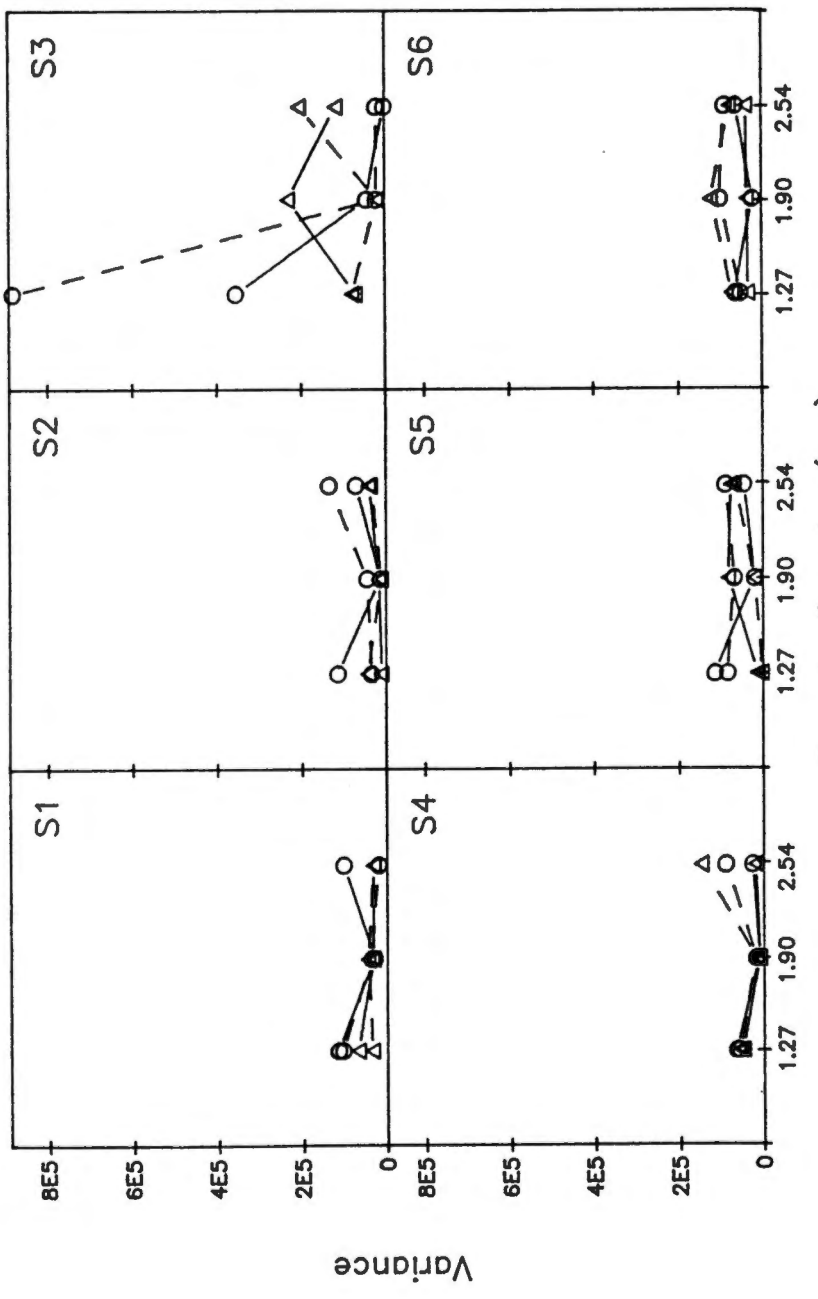


Figure IV.44 - Variance of the frequency of the second formant of sounds for the first and second chews as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions).

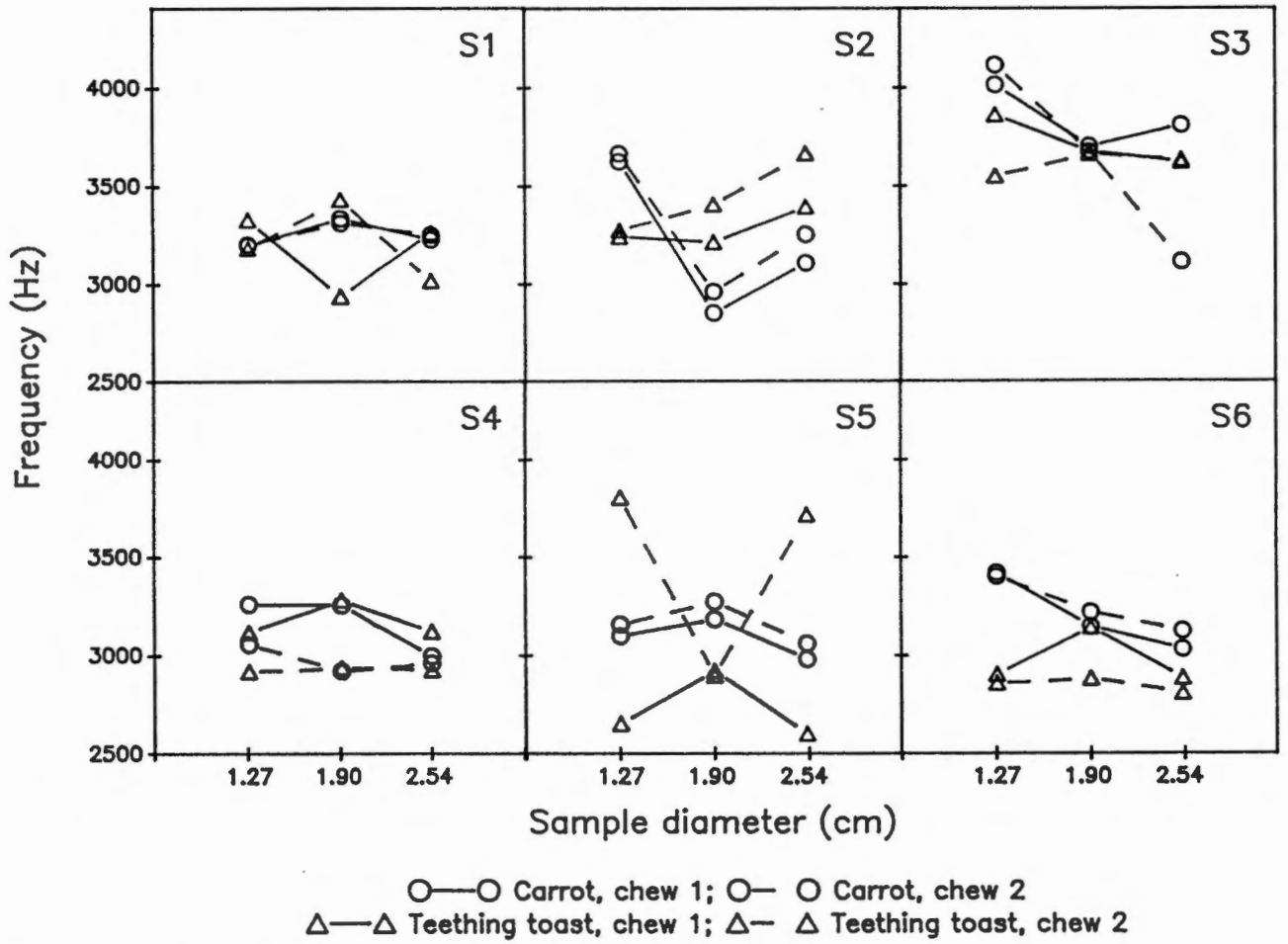


Figure IV.45 – Frequency of the third formant of sounds for the first and second chews as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions).

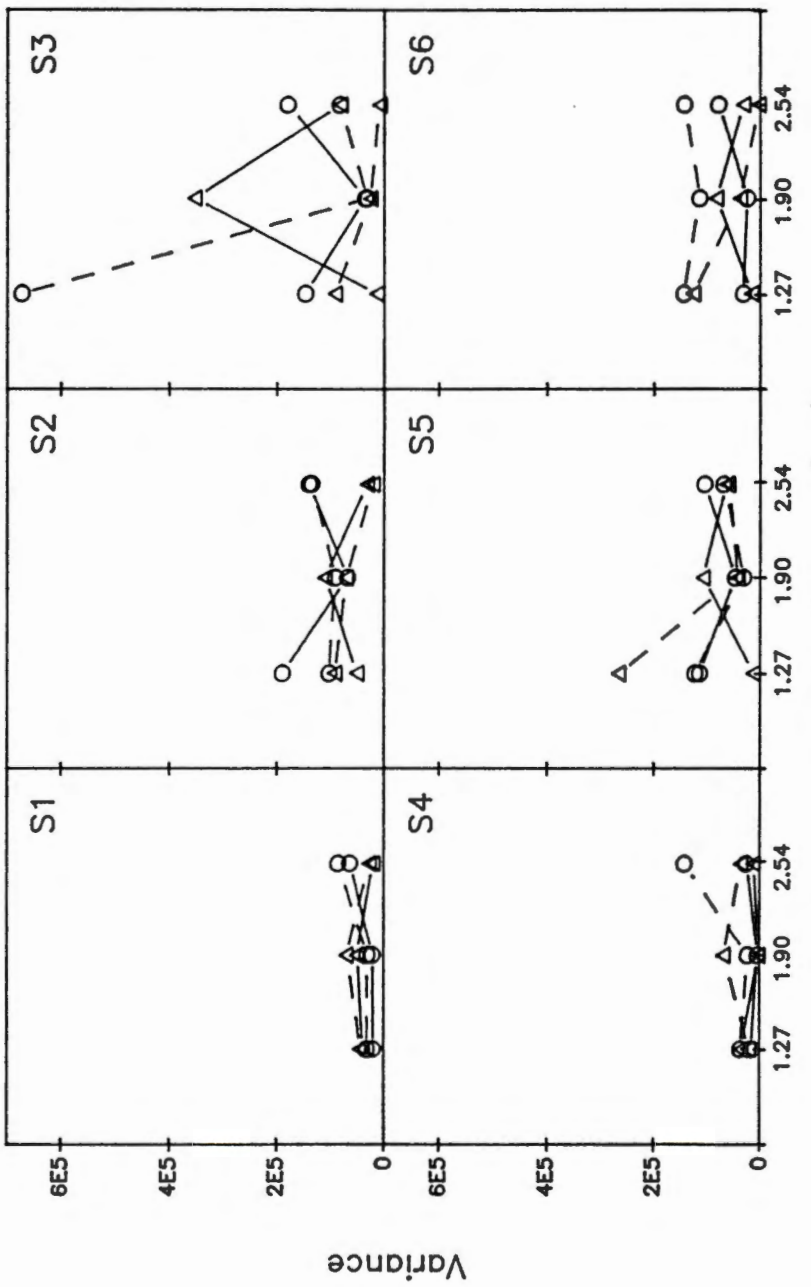


Figure IV.46 – Variance of the frequency of the third formant of sounds for the first and second chews as a function of subject (S1-S6) x food x sample diameter (n=10 repetitions).

In general, results indicated that variation in acoustical measures tended to be greater for the carrot samples than for the teething toast samples. Additionally, this variation tended to be related to the 1.27-cm samples. These results may be related to the inherent variability of carrots vs the uniformity of teething toast, a manufactured food. Results also may be related to the inherent variability of mastication. Ash (1984) and Ramfjord and Ash (1983) reported that type of food affects chewing cycle patterns and jaw muscle activities that control mastication.

Results also indicated that variation in acoustical measures tended to be greater for sounds produced by subjects 3 and 6 than for sounds produced by subjects 1, 2, 4, and 5. Again, these results may be related to the inherent variability of mastication. Furthermore, results emphasize the need for evaluating the oral status of subjects and for developing procedures for screening and selecting subjects for studies of mastication sounds. Boyar and Kilcast (1986b) and Heath and Lucas (1987) suggested the assessment of oral status of individuals participating in studies of mastication because oral status influences chewing cycle patterns.

4. CONCLUSIONS

The most important finding of this experiment concerned the nature of the variability in acoustical measures of mastication sounds. Analysis of estimates of variation in the measures revealed that intrasubject variability was inconsistent. In other words, variation within a subject was not the same for all 6 subjects in the experiment. Type of food and diameter of the food sample also affected the estimates of variation, indicating the variable nature of mastication. Generally, intrasubject variability was greater than intersubject variability. Additionally, analysis of ranks of the acoustical measures revealed that the effect of diameter of the food samples on the acoustical measures was inconsistent and depended on the subject producing the sounds and on the type of food. Because of this variability, characteristics of the subjects, including volume

of the oral cavity and acoustical characteristics of vowels, could not be related to acoustical measures of the mastication sounds.

If inferences are to be made concerning food texture from acoustical measures of mastication sounds, variability in these measures must be reduced. Inherent variability of the food samples and of mastication are possible sources of variation. In this experiment, a variety of experimental techniques was used to try to reduce the effects of these sources on the acoustical measures. Although coefficients of variation indicated that spectrographic measures of the sounds were reliable, intrasubject variability in the measures was inconsistent and frequently was greater than the intersubject variability. Therefore, research is needed to develop methods for reducing the effects of sources of variation on acoustical measures. Possible areas for research include developing criteria for screening and selecting subjects for study, establishing uniform procedures for mastication of food samples, defining dimensions for food samples, and identifying factors that may covary with acoustical measures.

Dental researchers have reported on the inherent variability of mastication. Ash (1984) and Ramfjord and Ash (1983) stated that dentition, type of occlusion, and presence of dysfunction affect the chewing cycle. Boyar and Kilcast (1986b) and Heath and Lucas (1987) emphasized the need for assessing the oral status of individuals participating in studies of mastication. Subjects in this experiment were selected, in part, based on results of dental examinations. The 6 subjects had normal occlusions and TMJs. In publications of mastication sounds by Drake (1965a,b) and Lee et al. (1988, 1990), the researchers stated that subjects reported having normal or natural dentition; however, the researchers did not report the status of the occlusions or TMJs of the subjects.

Subjects in this experiment also were selected based on similarities of chewing rates because results of the first experiment (Chapter III) in this study indicated that duration of mastication sounds varied with subjects. Differences were attributed to differences in chewing rates of the subjects. The procedure

described by Bourne (1985) was used to evaluate chewing rates of the subjects in this experiment. Briefly, chewing rates were the number of chews/min for chewing gum masticated to a "steady state". However, analysis of the durations of mastication sounds revealed variability in measures of duration. In future studies, spectrographic measures of duration should be evaluated as a method of assessing chewing rates of subjects. This evaluation should be performed with the food samples to be used in the experiment.

Another possibility is to control chewing rates of subjects. Lee et al. (1988, 1990), in studies of the intensities and spectral characteristics of mastication sounds, used a flashing light metronome as a cue for subjects to chew food samples. Although this technique may provide a means for controlling chewing rates, its benefits should be examined prior to its use because the researchers did not report variability in acoustical measures.

In studies of mastication sounds, food scientists have used different procedures for mastication of food samples. Drake (1963) evaluated sounds for samples of crisp brown bread for subjects who chewed the samples with the mouth open. Lee et al. (1988) also used this procedure to study spectral characteristics of sounds for fresh and stale samples of potato chips and tortilla chips. Additionally, Lee et al. (1990) studied the intensity of sounds produced by subjects who chewed the same type of food samples with their mouths open and with their mouths closed. However, the manner in which the chewing forces were applied to the food samples was not specified in reports of these studies. In contrast, Vickers (1984b, 1987) and Edmister and Vickers (1985) examined noise bursts of mastication sounds for the first bite of food samples between the incisors and subsequent chews between the molars.

In this experiment, subjects oriented cylindrical samples of food between the molar teeth so that the flat surfaces of the cylinders were parallel to the surfaces of the molars. Subjects also chewed the samples between the molars and with the mouth open. Subjects chewed the samples between the molars because this is the procedure for the Texture Profile Method for evaluating hardness of

foods (Brandt et al., 1963; Muñoz, 1986). Additionally, the open-mouth procedure was used to maximally capture sounds for recording. All sounds were recorded in a sound treated booth to reduce the level of environmental noise which could interfere with acoustical analysis of the mastication sounds.

Cardello and Seagers (1989) recently reported on the need for keeping the sizes of food samples uniform in studies of food texture. The researchers found that sample size affected sensory evaluation scores of hardness and chewiness. Drake (1965b) also suggested that sample size affected acoustical measures of mastication sounds. In this experiment, uniform sample dimensions were maintained. Cylindrical samples of raw carrot and teething toast were prepared for comparison of acoustical measures of sounds for the two types of food. Additionally, 3 diameters of the samples were prepared to examine the effect of sample diameter on acoustical measures. Results indicated that the variation in acoustical measures tended to be greater for the carrot samples than for the teething toast samples. Results also indicated that variation in acoustical measures tended to be greater for the 1.27-cm samples than for the 1.90- and 2.54-cm samples.

In future studies, statistical techniques for controlling the variability in acoustical measures of mastication sounds should be investigated. A review of the studies of mastication sounds indicates that a minimal number of sound samples has been examined for each subject in the studies. Furthermore, variability in acoustical measures was not reported for these studies. Drake (1963, 1965a,b) examined 4-5 repetitions per subject for each food sample. Lee et al. (1988, 1990) examined 2 repetitions per subject. In contrast, Vickers (1984b) and Edmister and Vickers (1985) analyzed sounds produced by 1 individual (one of the investigators). In this study, 10 repetitions per subject were analyzed for each food sample. However, results indicated an inconsistent intrasubject variation in acoustical measures despite experimental techniques that were used to control sources of variation. Therefore, a larger number of

repetitions per subject may need to be used in future studies to stabilize intrasubject variability.

Finally, the use of various statistical methods which control sources of variation and improve the precision of experiments should be investigated in future studies. Two methods which may be beneficial in studies of mastication sounds include experimental designs, particularly the block designs, and the analysis of covariance technique. In block designs, experimental units are grouped to form blocks which make the units comparable. For analysis of covariance, characteristics that may covary with a dependent variable of interest are measured. Means of the dependent variable then are adjusted for differences in means of the covariate. This technique is useful particularly when certain sources of variation can not be effectively controlled in an experiment (Cochran and Cox, 1957; Steel and Torrie, 1960). However, criteria for grouping and covariates of acoustical measures must be identified if these methods are to be used in studies of mastication sounds.

In this experiment, characteristics of the subjects were evaluated to provide descriptions of the subjects. These characteristics included the volume of the oral cavity and acoustical characteristics of vowels. These characteristics were evaluated because mastication sounds are similar to speech sounds in that they are produced within the oral cavity. Acoustical characteristics of speech sounds depend, in part, on the size of the oral cavity. Therefore, measures of these characteristics and measures of chewing rates may be potential criteria for forming blocks in studies of mastication sounds, or they may be potential covariates of acoustical measures of the sounds. Although this experiment was not designed for use of analysis of covariance, this type of information will be needed in future studies to identify criteria for grouping and to identify covariates for acoustical measures of mastication sounds.

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LIST OF REFERENCES

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APPENDIXES

APPENDIX A

CALCULATIONS FOR MEASURES OF COMPRESSION RATES AND DECIBELS

I. Determination of Compression Rates for the subjects (Bourne, 1985)

compression rate = (number of chews/min) (2 x distance in cm/chew)

II. Equation for Converting Amplitude in mv to Amplitude in dB (Fletcher, 1953)

$$dB = 20 \log R$$

R=(amplitude of mastication sounds in mv/amplitude of calibration tone in mv)

APPENDIX B

ANALYSIS OF VARIANCE TABLES

Table B.1 – Mean squares (ms) and F values for Instron parameters of the food samples

Parameter Source of variation	df	ms	F value
Hardness			
Food	1	17088.53	804.11***
Size	2	5307.83	249.76***
Food*Size	2	3443.89	162.05***
Error	114	21.25	
Fracturability			
Food	1	60363.62	1788.13***
Size	2	10189.49	301.84***
Food*Size	2	9884.34	292.80***
Error	114	33.76	
Peak force			
Food	1	45326.31	1300.43***
Size	2	13791.48	395.68***
Food*Size	2	6880.31	197.40***
Error	114	34.86	
Distance to peak			
Food	1	17.18	371.20***
Size	2	0.98	21.15***
Error	116	0.05	

*** $p < 0.001$.

Table B.2 – Mean squares (ms) and F values for oral-cavity volume of the subjects

Source of variation	df	ms	F value
Subject	5	4740.02	221.94***
Method	1	3876.04	181.49***
Subject*Method	5	576.24	26.98***
Error	84	21.36	

*** $p < 0.001$.

Table B.3 – Mean squares (ms) and probabilities (p) for F-values for variances of amplitude display parameters for sounds of the initial 2 chews of food samples

Dependent variable Source of variation	df	Chew 1		Chew 2	
		ms	p	ms	p
Duration					
Size	2	1.172E+08	0.103	40844858	0.002
Food	1	1.892E+08	0.056	1894847	0.476
Size*Food	2	1.597E+07	0.685	1114155	0.732
Subject	5	2.527E+08	0.007	22256769	0.006
Size*Subject	10	8.347E+07	0.136	3945766	0.419
Food*Subject	5	5.316E+07	0.335	4368748	0.351
Error	10	4.063E+07		3458021	
Peak amplitude					
Size	2	5.15	0.373	222.99	0.004
Food	1	16.90	0.088	37.54	0.218
Size*Food	2	13.68	0.102	2.99	0.873
Subject	5	6.44	0.316	8.67	0.838
Size*Subject	10	2.76	0.795	21.78	0.498
Food*Subject	5	2.91	0.691	14.20	0.666
Error	10	4.72		21.70	
Average amplitude					
Size	2	3.44	0.859	26.60	0.479
Food	1	58.28	0.137	96.63	0.121
Size*Food	2	20.03	0.438	83.83	0.132
Subject	5	10.11	0.802	44.42	0.333
Size*Subject	10	8.62	0.952	54.21	0.231
Food*Subject	5	14.88	0.657	89.72	0.087
Error	10	22.29		33.58	

Table B.4 – Mean squares (ms) and probabilities (p) for F-values variances of duration parameters for sounds of the initial 2 chews of food samples

Dependent variable Source of variation	df	ms	p
Duration of chew 1			
Size	2	8.087E+07	0.406
Food	1	4.641E+08	0.039
Size*Food	2	2.291E+07	0.762
Subject	5	2.151E+08	0.091
Size*Subject	10	7.502E+07	0.554
Food*Subject	5	4.387E+07	0.746
Error	10	8.193E+07	
Duration of chew 2			
Size	2	7341304	0.024
Food	1	94434	0.795
Size*Food	2	4061203	0.092
Subject	5	12458431	0.002
Size*Subject	10	1604580	0.385
Food*Subject	5	464727	0.871
Error	10	1326685	
Time from onset of chew 1 to onset of chew 2			
Size	2	3.981E+08	0.048
Food	1	8.209E+07	0.375
Size*Food	2	1.130E+08	0.345
Subject	5	2.478E+09	0.000
Size*Subject	10	6.213E+08	0.003
Food*Subject	5	3.447E+08	0.040
Error	10	9.518E+08	
Time from end of chew 1 to onset of chew 2			
Size	2	1.548E+07	0.763
Food	1	6.318E+08	0.007
Size*Food	2	2.652E+07	0.635
Subject	5	4.585E+08	0.003
Size*Subject	10	1.344E+08	0.091
Food*Subject	5	1.258E+08	0.128
Error	10	5.577E+07	
Time from onset of chew 1 to end of chew 2			
Size	2	4.172E+08	0.172
Food	1	1.645E+08	0.383
Size*Food	2	3.684E+08	0.205
Subject	5	2.271E+09	0.001
Size*Subject	10	5.085E+08	0.076
Food*Subject	5	5.626E+08	0.075
Error	10	1.974E+08	

Table B.5 – Mean squares (ms) and probabilities (p) for F-values for variances of formant frequencies (F1-F5) of sounds for the initial 2 chews of food samples

Dependent variable Source of variation	df	Chew 1		Chew 2	
		ms	p	ms	p
F1					
Size	2	9779638	0.816	9850100	0.837
Food	1	333752301	0.024	217027459	0.074
Size*Food	2	66844598	0.288	16789843	0.741
Subject	5	79557197	0.226	32514023	0.703
Size*Subject	10	47897974	0.492	23143359	0.903
Food*Subject	5	42597536	0.516	20685551	0.851
Error	10	4.724E+07		54362436	
F2					
Size		6.221E+09	0.275	1.974E+10	0.450
Food	1	3.136E+09	0.409	2.086E+10	0.361
Size*Food	2	1.540E+10	0.065	2.620E+10	0.355
Subject	5	9.522E+09	0.128	2.188E+10	0.486
Size*Subject	10	1.624E+09	0.926	2.166E+10	0.532
Food*Subject	5	4.752E+08	0.987	1.029E+10	0.804
Error	10	4.224E+09		2.280E+10	
F3					
Size	2	1.045E+09	0.788	1.783E+10	0.204
Food	1	1.151E+09	0.616	4.154E+10	0.063
Size*Food	2	2.040E+10	0.035	1.082E+10	0.360
Subject	5	1.164E+10	0.084	9.052E+09	0.491
Size*Subject	10	1.467E+09	0.947	1.342E+10	0.299
Food*Subject	5	1.663E+09	0.846	9.330E+09	0.476
Error	10	4.291E+09		9.532E+09	
F4					
Size	2	4.499E+09	0.593	5.906E+09	0.563
Food	1	8.024E+09	0.345	4.970E+10	0.046
Size*Food	2	6.999E+09	0.453	1.542E+10	0.249
Subject	5	3.548E+10	0.023	1.745E+11	0.000
Size*Subject	10	5.323E+09	0.744	6.172E+09	0.752
Food*Subject	5	3.554E+09	0.814	1.546E+10	0.244
Error	10	8.160E+09		9.616E+10	
F5					
Size	2	1.791E+09	0.922	9.160E+10	0.460
Food	1	2.149E+09	0.761	6.910E+10	0.445
Size*Food	2	1.607E+10	0.506	2.726E+10	0.784
Subject	5	6.400E+10	0.071	1.352E+11	0.360
Size*Subject	10	8.290E+09	0.930	8.287E+10	0.664
Food*Subject	5	3.030E+10		1.127E+11	0.450
Error	10	2.201E+10		1.091E+11	

Table B.6 – Mean squares (ms) and probabilities (p) for F-values for variances of formant amplitudes (F1-F5) of sounds for the initial 2 chews of food samples

Dependent variable Source of variation	df	Chew 1		Chew 2	
		ms	p	ms	p
F1					
Size	2	3.31	0.931	5.33	0.940
Food	1	124.03	0.132	916.63	0.008
Size*Food	2	0.80	0.983	107.54	0.323
Subject	5	158.32	0.046	24.86	0.906
Size*Subject	10	61.97	0.324	65.61	0.654
Food*Subject	5	46.84	0.457	187.63	0.134
Error	10	46.05		84.82	
F2					
Size	2	87.83	0.616	170.98	0.433
Food	1	429.49	0.146	673.69	0.087
Size*Food	2	406.83	0.145	112.89	0.567
Subject	5	277.10	0.245	257.50	0.313
Size*Subject	10	93.75	0.826	171.13	0.557
Food*Subject	5	199.02	0.396	61.40	0.886
Error	10	172.83		187.75	
F3					
Size	2	109.29	0.045	68.00	0.287
Food	1	195.89	0.020	202.46	0.067
Size*Food	2	18.09	0.513	115.91	0.139
Subject	5	71.29	0.077	30.59	0.677
Size*Subject	10	33.29	0.338	45.41	0.534
Food*Subject	5	91.24	0.040	31.99	0.658
Error	10	25.36		47.98	
F4					
Size	2	28.89	0.444	26.96	0.467
Food	1	27.09	0.384	29.95	0.361
Size*Food	2	103.63	0.086	30.15	0.430
Subject	5	44.01	0.322	78.72	0.111
Size*Subject	10	37.91	0.411	40.80	0.367
Food*Subject	5	23.99	0.615	50.95	0.258
Error	10	32.74		32.75	
F5					
Size	2	42.85	0.150	0.71	0.978
Food	1	253.90	0.004	96.63	0.109
Size*Food	2	18.88	0.397	10.30	0.727
Subject	5	40.08	0.141	9.74	0.895
Size*Subject	10	18.34	0.508	27.76	0.573
Food*Subject	5	32.24	0.215	7.20	0.941
Error	10	18.59		31.26	

Table B.7 – Mean squares (ms) and probabilities (p) for F-values for variances of oscilloscopic parameters for sounds of the initial 2 chews of food samples

Dependent variable Source of variation	df	Chew 1		Chew 2	
		ms	p	ms	p
Duration					
Size	2	58731257	0.018	29037628	0.001
Food	1	84019494	0.014	1184735	0.446
Size*Food	2	2799073	0.750	1357273	0.510
Subject	5	117150884	0.001	29604664	0.000
Size*Subject	10	34090922	0.028	4381460	0.100
Food*Subject	5	11611609	0.365	1577915	0.552
Error	10	9.455E+06		1881654	
Peak time					
Size	2	15585467	0.302	2848509	0.089
Food	1	26103317	0.163	4592496	0.049
Size*Food	2	2531054	0.806	1157958	0.323
Subject	5	27707005	0.111	14259754	0.000
Size*Subject	10	13916224	0.385	1651869	0.182
Food*Subject	5	16179860	0.301	1352822	0.279
Error	10	11503888		913680	
Peak amplitude					
Size	2	0.6665	0.221	52.12	0.040
Food	1	0.1762	0.511	1.40	0.735
Size*Food	2	0.3918	0.390	1.62	0.871
Subject	5	1.8067	0.017	6.98	0.698
Size*Subject	10	0.7195	0.163	4.46	0.925
Food*Subject	5	0.8152	0.141	5.10	0.809
Error	10	0.3786		11.52	

Table B.8 – Mean squares (ms) and probabilities (p) for F-values for ranks of variances for amplitude display parameters for sounds of the initial 2 chews of food samples

Dependent variable Source of variation	df	Chew 1		Chew 2	
		ms	p	ms	p
Duration					
Size	2	589.75	0.21	2574.25	0.00
Food	1	1013.36	0.11	7.11	0.86
Size*Food	2	125.69	0.69	63.19	0.75
Subject	5	1999.52	0.01	1404.13	0.01
Size*Subject	10	522.82	0.23	239.98	0.42
Food*Subject	5	199.16	0.69	208.98	0.47
Error	10	324.29		209.06	
Peak amplitude					
Size	2	512.51	0.45	4787.55	0.00
Food	1	2450.25	0.07	2450.25	0.02
Size*Food	2	1185.90	0.19	103.65	0.74
Subject	5	868.96	0.28	72.91	0.95
Size*Subject	10	428.27	0.69	455.66	0.31
Food*Subject	5	479.63	0.57	153.55	0.79
Error	10	591.73		328.97	
Average amplitude					
Size	2	245.58	0.68	2552.33	0.03
Food	1	1600.00	0.14	1213.36	0.14
Size*Food	2	495.25	0.48	798.78	0.24
Subject	5	418.60	0.65	350.18	0.62
Size*Subject	10	271.18	0.90	389.27	0.63
Food*Subject	5	675.27	0.42	1567.96	0.05
Error	10	622.12		480.98	

Table B.9 – Mean squares (ms) and probabilities (p) for F-values for ranks of variances for duration parameters for sounds of the initial 2 chews of food samples

Dependent variable Source of variation	df	ms	p
Duration of chew 1			
Size	2	328.44	0.58
Food	1	2880.11	0.05
Size*Food	2	155.44	0.76
Subject	5	1591.18	0.08
Size*Subject	10	320.01	0.81
Food*Subject	5	307.58	0.74
Error	10	562.41	
Duration of chew 2			
Size	2	1180.53	0.04
Food	1	13.44	0.83
Size*Food	2	706.03	0.12
Subject	5	2186.64	0.00
Size*Subject	10	324.46	0.38
Food*Subject	5	32.31	0.98
Error	10	267.29	
Time from onset of chew 1 to onset of chew 2			
Size	2	768.03	0.07
Food	1	34.03	0.70
Size*Food	2	181.86	0.46
Subject	5	2156.69	0.00
Size*Subject	10	468.03	0.12
Food*Subject	5	470.63	0.14
Error	10	217.46	
Time from end of chew 1 to onset of chew 2			
Size	2	627.08	0.23
Food	1	3402.78	0.01
Size*Food	2	727.86	0.19
Subject	5	1862.13	0.01
Size*Subject	10	307.32	0.62
Food*Subject	5	234.98	0.68
Error	10	372.96	
Time from onset of chew 1 to end of chew 2			
Size	2	654.69	0.12
Food	1	87.11	0.57
Size*Food	2	329.53	0.31
Subject	5	2003.58	0.00
Size*Subject	10	365.76	0.28
Food*Subject	5	498.24	0.17
Error	10	250.86	

Table B.10 – Mean squares (ms) and probabilities (p) for F-values for ranks of variances for formant (F1-F5) frequencies of sounds for the initial 2 chews of food samples

Dependent variable Source of variation	df	Chew 1		Chew 2	
		ms	p	ms	p
F1					
Size	2	168.78	0.59	133.78	0.80
Food	1	2652.25	0.01	2401.00	0.07
Size*Food	2	603.58	0.18	221.08	0.70
Subject	5	1019.26	0.05	355.58	0.71
Size*Subject	10	328.51	0.44	224.01	0.93
Food*Subject	5	343.10	0.40	253.67	0.82
Error	10	297.78		601.05	
F2					
Size	2	1303.86	0.04	1241.86	0.13
Food	1	361.00	0.29	529.00	0.33
Size*Food	2	2090.08	0.01	325.75	0.54
Subject	5	921.64	0.06	485.58	0.48
Size*Subject	10	191.13	0.75	755.56	0.26
Food*Subject	5	445.87	0.27	430.26	0.54
Error	10	294.35		499.92	
F3					
Size	2	136.78	0.68	692.33	0.11
Food	1	476.69	0.26	3061.78	0.00
Size*Food	2	2284.11	0.01	1348.78	0.02
Subject	5	1487.16	0.02	461.07	0.16
Size*Subject	10	144.31	0.90	449.90	0.15
Food*Subject	5	162.23	0.79	237.04	0.45
Error	10	341.64		230.94	
F4					
Size	2	114.11	0.69	227.86	0.18
Food	1	961.00	0.10	1248.44	0.01
Size*Food	2	181.00	0.56	306.69	0.11
Subject	5	1976.11	0.01	3270.84	0.00
Size*Subject	10	277.01	0.54	177.59	0.24
Food*Subject	5	610.53	0.15	229.11	0.16
Error	10	294.03		111.56	
F5					
Size	2	360.75	0.49	316.33	0.47
Food	1	1906.78	0.07	96.69	0.63
Size*Food	2	65.36	0.87	115.11	0.75
Subject	5	1709.40	0.04	1966.98	0.01
Size*Subject	10	221.05	0.87	443.97	0.43
Food*Subject	5	677.38	0.29	415.69	0.44
Error	10	468.06		393.81	

Table B.11 – Mean squares (ms) and probabilities (p) for F-values for ranks of variances for formant (F1-F5) amplitudes of sounds for the initial 2 chews of food samples

Dependent variable Source of variation	df	Chew 1		Chew 2	
		ms	p	ms	p
F1					
Size	2	110.25	0.77	16.75	0.96
Food	1	1573.44	0.08	4117.36	0.01
Size*Food	2	263.36	0.55	466.86	0.40
Subject	5	1247.00	0.06	101.25	0.95
Size*Subject	10	572.55	0.32	353.95	0.67
Food*Subject	5	221.91	0.75	788.09	0.22
Error	10	421.13		466.79	
F2					
Size	2	420.58	0.35	350.58	0.52
Food	1	940.44	0.14	3680.44	0.02
Size*Food	2	1402.86	0.06	107.53	0.81
Subject	5	770.93	0.14	634.28	0.36
Size*Subject	10	248.42	0.72	810.67	0.24
Food*Subject	5	478.31	0.33	243.93	0.78
Error	10	360.23		508.81	
F3					
Size	2	2023.97	0.02	1847.86	0.08
Food	1	3098.78	0.01	2288.03	0.07
Size*Food	2	77.42	0.80	1326.36	0.15
Subject	5	732.69	0.15	408.03	0.63
Size*Subject	10	317.91	0.55	669.96	0.41
Food*Subject	5	853.14	0.10	408.69	0.63
Error	10	345.22		578.93	
F4					
Size	2	547.58	0.49	285.36	0.65
Food	1	455.11	0.45	373.78	0.46
Size*Food	2	2172.53	0.09	1058.36	0.24
Subject	5	973.87	0.32	1272.98	0.17
Size*Subject	10	672.85	0.54	919.36	0.29
Food*Subject	5	664.64	0.51	685.91	0.43
Error	10	721.26		644.09	
F5					
Size	2	42.85	0.15	0.71	0.98
Food	1	253.90	0.00	96.63	0.11
Size*Food	2	18.88	0.40	10.30	0.73
Subject	5	40.08	0.14	9.74	0.89
Size*Subject	10	18.34	0.51	27.76	0.57
Food*Subject	5	32.24	0.21	7.20	0.94
Error	10	18.59		31.26	

Table B.12 – Mean squares (ms) and probabilities (p) for F-values for ranks of variances for oscilloscopic parameters for sounds of the initial 2 chews of food samples

Dependent variable Source of variation	df	Chew 1		Chew 2	
		ms	p	ms	p
Duration					
Size	2	914.33	0.02	2605.75	0.00
Food	1	1167.36	0.02	44.44	0.67
Size*Food	2	24.11	0.86	160.53	0.52
Subject	5	1868.05	0.00	2496.67	0.00
Size*Subject	10	610.13	0.02	191.62	0.62
Food*Subject	5	51.83	0.88	238.04	0.45
Error	10	156.58		233.13	
Peak time					
Size	2	267.11	0.12	605.19	0.06
Food	1	633.36	0.03	625.00	0.08
Size*Food	2	204.78	0.18	140.58	0.45
Subject	5	1425.83	0.00	2846.71	0.00
Size*Subject	10	535.11	0.01	564.43	0.03
Food*Subject	5	408.63	0.03	558.13	0.04
Error	10	99.84		160.62	
Peak amplitude					
Size	2	494.36	0.16	4791.08	0.01
Food	1	12.25	0.82	78.03	0.74
Size*Food	2	203.08	0.43	170.36	0.78
Subject	5	1493.83	0.01	419.38	0.69
Size*Subject	10	798.46	0.03	401.92	0.79
Food*Subject	5	392.85	0.21	45.43	0.99
Error	10	223.38		676.66	

Table B.13 - Mean squares (ms) and F values for ranks of amplitude display parameters for sounds of the initial 2 chews of food samples

		Chew 1		Chew 2	
Source of variation	df	ms	F value	ms	F value
Average amplitude					
Size	2	10165.19	0.57	66122.32	3.15
Food	1	676196.14	18.84**	120733.32	2.99
Subject	5	185870.23	35.65***	79519.00	9.89***
Size*subject[a]	10	17890.27	3.43**	21024.47	2.62**
Food*subject[b]	5	35885.29	6.88***	40370.57	5.02***
Food*size*subject	12	8495.95	1.63	16327.06	2.03*
Error	320(323)[c]	5213.10	8038.50		
Peak amplitude					
Size	2	97132.70	6.56*	536716.70	15.60***
Food	1	27.30	0.00	238.00	0.00
Subject	5	225350.50	38.67***	33058.60	6.33***
Size*subject[a]	10	14810.40	2.54**	34414.70	6.59***
Food*subject[b]	5	31500.80	5.41***	48870.60	9.33***
Food*size*subject	12	9766.93	1.68	24431.63	4.70***
Error	320(323)[c]	5827.30		5224.00	
Time					
Size	2	139127.60	4.50*		
Food	1	20303.80	2.22		
Subject	5	236441.20	41.93***		
Size*subject[a]	10	30946.50	5.49***		
Food*size*subject[b]	17	9147.21	1.60		
Error	320	5639.40			
Time					
Size	2			289116.30	11.55**
Food	1			11479.30	0.21
Subject	5			257131.10	66.54***
Size*subject[a]	10			25040.00	6.48***
Food*subject[b]	5			55346.90	14.32***
Food*size*subject	12			17121.60	4.40***
Error	323			3864.20	

*p<0.05.
**p<0.01.
***p<0.001.
[a]Error term for size.
[b]Error term for food.
[c]Degrees of freedom for chew 2 in ().

Table B.14 – Mean squares (ms) and F values for ranks of frequency and amplitude of formants 1-5 for sounds of the initial 2 chews of food samples

		Chew 1		Chew 2	
Source of variation	df	ms	F value	ms	F value
Frequecy data					
Formant 1					
Size	1	291578.90	24.07**	358728.70	13.21**
Food	1	4084.00	0.18	140240.10	3.60
Subject	5	370968.30	122.98***	220024.00	57.63***
Size*subject[a]	10	12115.70	4.02**	27146.70	7.11***
Food*subject[b]	5	22349.10	7.41**	38949.40	10.20***
Food*size*subject	12	6556.67	2.17*	11153.63	2.92**
Error	320	3016.40	3817.70		
Formant 2					
Size	2	18776.57	0.35	81012.95	2.94
Food	1	419893.62	5.82	37419.10	0.82
Subject	5	9311.37	13.50***	149193.01	23.81***
Size*subject[a]	10	53094.80	10.34***	27579.11	4.40***
Food*subject[b]	5	72121.74	14.05***	45776.8	7.31***
Food*size*subject	12	33051.03	6.44**	26679.56	4.26***
Error	320(321)[c]	5134.60	6266.40		
Formant 3					
Size	1	89921.74	2.47	27321.50	1.04
Food	1	29569.02	0.63	660.20	0.01
Subject	5	141239.68	27.43***	17769.10	46.72***
Size*subject[a]	10	36338.01	7.06***	26204.10	5.62***
Food*subject[b]	5	47223.45	9.17***	64395.80	13.82***
Food*size*subject	12	48045.06	9.33***	43371.08	9.31***
Error	320	5149.70		4661.00	
Formant 4					
Size	2	70161.92	0.62	3331.14	0.23
Food	1	5563.68	0.30	381.64	0.01
Subject	5	169960.63	28.60***	172866.22	28.56***
Size*subject[a]	10	19377.79	3.26***	14310.68	2.36
Food*subject[b]	5	18606.85	3.13**	34929.63	5.77***
Food*size*subject	12	38154.35	6.42***	28499.75	4.71***
Error	320(308)[c]	5943.20		6052.10	

continued

Table B.14 – (continued)

Source of variation	df	Chew 1 ms	Chew 1 F value	Chew 2 ms	Chew 2 F value
Formant 5					
Size	2	52739.65	2.43	9588.01	0.91
Food	1	10192.94	0.25	1178.86	0.10
Subject	5	48902.16	31.51***	158943.99	35.38***
Size*subject[a]	10	21731.09	4.60***	10589.18	2.36*
Food*subject[b]	5	40987.14	8.67***	11944.55	2.66*
Food*size*subject	12	23789.86	5.03**	12800.74	2.85**
Error	292(272)[c]	4725.40		4492.70	
Amplitude					
Formant 1					
Size	2	903.72	0.07	565471.30	3.62
Food	1	76393.89	9.29**	1479981.00	29.35**
Subject	5	05013.69	15.82***	18255.70	3.73***
Size*subject[a]	10	12912.84	1.95*	15625.60	3.20***
Food*subject[b]	5	29754.20	4.48***	50418.80	10.31***
Food*size*subject	12	3808.49	6.60**	10952.67	2.24**
Error	322(320)[c]	6637.00		4890.00	
Formant 2					
Size	2	47872.60	2.15		
Food	1	331348.50	1.68*		
Subject	5	301374.20	0.02***		
Size*subject[a]	10	22260.10	5.91***		
Food*subject[b]	5	28357.00	7.53***		
Food*size*subject	12	19816.18	5.26***		
Error	320	3766.40			
Formant 2					
Size	2			240408.29	9.12*
Food	1			7781.95	0.69*
Subject	5			157298.49	23.83***
Size*subject[a]	10			26348.75	3.99**
Error[b]	338			6601.30	
Formant 3					
Size	2	694.10	0.32	127837.85	7.74*
Food	1	454.40	0.10	36958.47	0.79
Subject	5	211648.70	30.79***	97404.65	3.25***
Size*subject[a]	10	14571.80	2.12**	16517.04	2.25*
Food*subject[b]	5	24449.80	3.56**	46559.11	6.33***
Food*size*subject	12	16279.57	2.37**	17224.82	2.34**
Error	320	6874.60		7351.30	

continued

Table B.14 - (continued)

Source of variation	df	Chew 1 ms	Chew 1 F value	Chew 2 ms	Chew 2 F value
Formant 4					
Size	2	64898.80	4.49		
Food	1	543.40	0.01		
Subject	5	88368.82	10.59***		
Food*subject[a]	5	42147.12	5.05***		
Error[b]	338	8344.49			
Formant 4					
Size	2			19447.73	6.98
Food	1			66.80	0.00
Subject	5			54644.62	7.06***
Size*subject[a]	10			17114.26	2.21*
Food*subject[b]	5			41252.05	5.33***
Error	320			7744.34	
Formant 5					
Size	2	8657.43	1.58		
Food	1	2877.61	2.00		
Subject	5	8990.26	7.42***		
Size*subject[a]	10	24392.33	3.69***		
Food*subject[b]	5	36359.37	5.51***		
Food*size*subject	12	7203.45	2.60**		
Error	284	6604.18			
Formant 5					
Size	1			10677.35	0.45
Food	1			1628.66	0.06
Subject	5			5545.82	0.82
Size*subject[a]	10			23571.31	3.48*
Food*subject[b]	5			28018.56	4.13*
Error	292			6776.21	

*p<0.05.
**p<0.01.
***p<0.001.
[a]Error term for size.
[b]Error term for food.
[c]Degrees of freedom for chew 2 in ().

Table B.15 – Mean squares (ms) and F values for ranks of duration parameters for sounds of the initial 2 chews of food samples

Source of variation		df	ms	F value
Between	Size	2	37485.00	1.73
	Food	1	196979.20	3.15
	Subject	5	212550.80	39.81***
	Size*subject[a]	10	21672.80	4.06***
	Food*subject[b]	5	62608.80	11.73***
	Food*size*subject	12	14670.05	2.75**
	Error	320	5339.30	
Chew 1	Size	2	192897.10	6.60*
	Food	1	48245.10	1.29
	Subject	5	246211.40	49.77*
	Size*subject[a]	10	29240.10	5.91***
	Food*size*subject[b]	17	37501.77	7.58***
	Error	320	4946.50	
Chew 2	Size	2	258991.40	11.62**
	Food	1	7358.10	.16
	Subject	5	309464.90	77.79***
	Size*subject[a]	10	22281.30	5.60***
	Food*subject[b]	5	46620.70	11.72***
	Error	323	3978.12	
Oonset	Size	2	124772.50	5.55*
	Food	1	9447.50	.59
	Subject	5	303429.80	66.75***
	Size*subject[a]	10	22465.70	4.94***
	Food*subject[b]	5	16008.90	3.52***
	Food*size*subject	12	8904.73	1.96*
	Error	320	4546.00	
Total	Size	2	195310.90	7.50*
	Food	1	10289.10	.43
	Subject	5	363236.80	118.11***
	Size*subject[a]	10	26045.60	8.47***
	Food*subject[b]	5	23971.80	7.79***
	Food*size*subject	12	6962.00	2.26**
	Error	320	3075.40	

*p<0.05.
**p<0.01.
***p<0.001.
[a]Error term for size.
[b]Error term for food.

Table B.16 - Mean squares (ms) and F values for ranks of oscilloscopic parameters for sounds of the initial 2 chews of food samples

		Chew 1		Chew 2	
Source of variation	df	ms	F value	ms	F value
Peak amplitude					
size	2	18133.70	0.68		
food	1	10576.30	0.58		
subject	5	316723.80	66.50***		
size*subject[a]	10	26535.10	5.57***		
food*subject[b]	5	18130.00	3.81**		
food*size*subject	12	20168.50	4.23***		
error	320	4763.00			
Peak amplitude					
size	2			310187.98	17.71***
food	1			18755.22	1.00
subject	5			165550.11	28.12***
size*subject[a]	10			17511.48	2.97**
food*size*subject[b]	17			18835.55	3.20***
error	323			5886.80	
Duration					
size	2	172109.15	6.64*	321471.20	16.64***
food	1	203222.29	5.59	1777.00	0.03
subject	5	192063.79	38.66***	238366.30	54.96***
size*subject[a]	10	25923.00	5.22***	19320.00	4.45***
food*subject[b]	5	36355.73	7.32***	55977.80	12.91***
food*size*subject	12	17027.40	3.43***	11468.48	2.64**
error	320(323)[c]	4967.70		4337.10	
Peak time					
size	2	88222.06	1.89	109768.35	7.18*
food	1	225386.86	7.61	26521.77	0.76
subject	5	104521.54	16.96***	116664.60	15.33***
size*subject[a]	10	46582.01	7.56***	15284.40	2.01*
food*subject[b]	5	29635.89	4.81***	34973.68	4.60***
food*size*subject	12	19175.84	3.11***	19557.66	2.57**
error	320(323)[c]	6164.40		7611.10	

*p<0.05.
**p<0.01.
***p<0.001.
[a]Error term for size.
[b]Error term for food.
[c]Degrees of freedom for chew 2 in ().

APPENDIX C

INTERACTION MEANS TABLES

Table C.1 – Food type x sample diameter interaction means ± standard deviations for Instron parameters for food samples (n=20 repetitions)

Parameter / Food	Diameter of sample (cm) 1.27	1.90	2.54
	(kg)		
Hardness			
Carrot	9.0 ± 3.1	21.7 ± 5.8	49.7 ± 9.0
Teething toast	1.0 ± 0.4	2.4 ± 0.7	5.4 ± 1.4
Fracturability			
Carrot	18.2 ± 2.6	40.0 ± 7.1	80.6 ± 12.0
Teething toast	1.1 ± 0.5	1.4 ± 1.1	1.6 ± 0.9
Peak force			
Carrot	18.2 ± 2.6	40.0 ± 7.1	80.6 ± 12.0
Teething toast	2.2 ± 0.9	6.8 ± 1.6	13.1 ± 2.3

Table C.2 – Subject x sample diameter interaction means ± standard deviations for amplitude display parameters for sounds of the first chew of food samples (n=10 repetitions)

Parameter / Subject	Diameter of sample (cm) 1.27	1.90	2.54
Average amplitude (dB)[a]			
1	-33 ± 4	-33 ± 4	-32 ± 4
2	-30 ± 3	-29 ± 4	-29 ± 3
3	-28 ± 5	-31 ± 4	-32 ± 4
4	-28 ± 3	-26 ± 3	-27 ± 3
5	-28 ± 3	-26 ± 3	-28 ± 3
6	-32 ± 3	-30 ± 4	-32 ± 3
Peak amplitude (dB)[a]			
1	-19 ± 2	-17 ± 2	-17 ± 2
2	-20 ± 2	-19 ± 2	-17 ± 1
3	-17 ± 3	-16 ± 2	-17 ± 2
4	-17 ± 2	-16 ± 1	-16 ± 1
5	-17 ± 1	-16 ± 1	-16 ± 1
6	-20 ± 2	-19 ± 2	-20 ± 2
Time (msec)			
1	365 ± 91	442 ± 99	473 ± 123
2	334 ± 69	332 ± 61	375 ± 68
3	299 ± 62	420 ± 165	515 ± 131
4	247 ± 46	243 ± 64	311 ± 75
5	364 ± 84	327 ± 69	404 ± 57
6	517 ± 134	435 ± 96	486 ± 184

[a]Amplitude relative to full scale output of the sound spectrograph.

Table C.3 – Subject x sample diameter interaction means ± standard deviations for amplitude (dB)[a] of formants 2, 4, and 5 for sounds of the second chew of food samples (n=10 repetitions)

Formant Subject	Diameter of sample (cm)		
	1.27	1.90	2.54
Formant 2			
1	-25 ± 5	-24 ± 5	-24 ± 4
2	-24 ± 3	-19 ± 4	-21 ± 5
3	-20 ± 7	-16 ± 4	-16 ± 6
4	-24 ± 3	-19 ± 3	-17 ± 4
5	-26 ± 5	-16 ± 4	-18 ± 5
6	-25 ± 6	-23 ± 5	-25 ± 3
Formant 4			
1	-27 ± 4	-22 ± 2	-22 ± 2
2	-24 ± 4	-21 ± 4	-22 ± 2
3	-27 ± 5	-26 ± 4	-25 ± 4
4	-26 ± 3	-23 ± 4	-22 ± 3
5	-23 ± 2	-23 ± 4	-22 ± 3
6	-24 ± 3	-23 ± 4	-23 ± 4
Formant 5			
1	-27 ± 3	-23 ± 3	-26 ± 3
2	-27 ± 3	-25 ± 4	-25 ± 3
3	-26 ± 4	-27 ± 3	-26 ± 4
4	-27 ± 4	-26 ± 2	-23 ± 3
5	-26 ± 2	-25 ± 4	-25 ± 3
6	-24 ± 4	-26 ± 3	-28 ± 4

[a]Amplitude relative to a calibration tone (1000 Hz, 80 dB).

Table C.4 – Subject x food type interaction means ± standard deviations for amplitude (dB)[a] of formant 4 for sounds of the first chew of food samples (n=10 repetitions)

	Type of food	
Subject	Carrot	Teething Toast
1	-20 ± 3	-23 ± 3
2	-23 ± 4	-22 ± 4
3	-25 ± 4	-26 ± 3
4	-23 ± 4	-20 ± 3
5	-23 ± 4	-24 ± 4
6	-24 ± 4	-24 ± 4

[a]Amplitude relative to a calibration tone (1000 Hz, 80 dB).

Table C.5 – Subject x food type interaction means ± standard deviations for amplitude (dB)[a] of formants 4 and 5 for sounds of the second chew of food samples (n=10 repetitions)

	Type of food	
Parameter Subject	Carrot	Teething Toast
Formant 4		
1	-23 ± 3	-23 ± 4
2	-24 ± 3	-21 ± 4
3	-27 ± 5	-25 ± 3
4	-24 ± 4	-24 ± 4
5	-21 ± 3	-24 ± 3
6	-23 ± 4	-24 ± 4
Formant 5		
1	-25 ± 3	-25 ± 3
2	-26 ± 3	-26 ± 3
3	-28 ± 3	-24 ± 3
4	-25 ± 3	-25 ± 4
5	-25 ± 3	-26 ± 3
6	-25 ± 3	-27 ± 3

[a]Amplitude relative to a calibration tone (1000 Hz, 80 dB).

Table C.6 – Subject x food type interaction means ± standard deviations for amplitude display parameters for sounds of the first chew of food samples (n=10 repetitions)

Parameter / Subject	Type of food: Carrot	Type of food: Teething Toast
	----------(dB)----------	
Average amplitude[a]		
1	-35 ± 2	-30 ± 2
2	-31 ± 2	-28 ± 3
3	-34 ± 3	-27 ± 4
4	-27 ± 3	-27 ± 2
5	-29 ± 3	-26 ± 2
6	-33 ± 3	-30 ± 3
Peak amplitude[a]		
1	-17 ± 2	-18 ± 2
2	-19 ± 2	-18 ± 2
3	-18 ± 2	-16 ± 2
4	-16 ± 2	-16 ± 1
5	-16 ± 2	-17 ± 1
6	-19 ± 2	-20 ± 2

[a]Amplitude relative to full scale output of the sound spectrograph.

Table C.7 – Subject x sample diameter x food type interaction means ± standard deviations for amplitude display parameters for sounds of the initial 2 chews of food samples (n=10 repetitions)

	Diameter of sample (cm)					
	Carrot			Teething toast		
Subject	1.27	1.90	2.54	1.27	1.90	2.54
	Time (msec)					
Chew 1						
1	324 ± 76	423 ± 88	433 ± 81	405 ± 91	461 ± 110	513 ± 148
2	323 ± 64	334 ± 54	366 ± 58	346 ± 76	330 ± 70	382 ± 78
3	293 ± 74	336 ± 71	539 ± 93	305 ± 50	504 ± 192	492 ± 162
4	237 ± 44	215 ± 52	313 ± 89	257 ± 48	270 ± 64	310 ± 64
5	361 ± 84	323 ± 51	414 ± 67	367 ± 88	330 ± 86	395 ± 47
6	538 ± 117	472 ± 106	441 ± 180	499 ± 153	399 ± 73	526 ± 188
Chew 2						
1	263 ± 38	317 ± 66	354 ± 104	206 ± 25	347 ± 73	385 ± 78
2	206 ± 31	258 ± 36	276 ± 32	160 ± 107	195 ± 14	219 ± 48
3	183 ± 45	266 ± 28	332 ± 70	191 ± 42	300 ± 63	332 ± 94
4	191 ± 43	197 ± 39	259 ± 50	185 ± 26	340 ± 61	269 ± 45
5	262 ± 41	283 ± 76	336 ± 65	344 ± 52	375 ± 46	428 ± 73
6	337 ± 71	386 ± 78	423 ± 111	390 ± 56	336 ± 78	323 ± 76
	Peak amplitude (dB)[a]					
Chew 1						
1	-18 ± 1	-17 ± 2	-16 ± 2	-19 ± 2	-18 ± 2	-18 ± 1
2	-20 ± 3	-19 ± 2	-17 ± 1	-20 ± 1	-18 ± 2	-18 ± 1
3	-19 ± 3	-16 ± 2	-19 ± 2	-16 ± 1	-17 ± 3	-16 ± 1
4	-16 ± 2	-15 ± 1	-17 ± 2	-17 ± 1	-16 ± 1	-16 ± 1
5	-17 ± 2	-16 ± 1	-16 ± 1	-18 ± 1	-16 ± 1	-16 ± 1
6	-20 ± 2	-20 ± 2	-19 ± 1	-20 ± 2	-18 ± 1	-20 ± 2
Chew 2						
1	-24 ± 3	-20 ± 3	-19 ± 2	-26 ± 5	-19 ± 1	-20 ± 1
2	-25 ± 4	-20 ± 1	-18 ± 2	-24 ± 4	-18 ± 1	-18 + 2
3	-22 ± 4	-21 ± 2	-21 ± 2	-19 ± 2	-21 ± 2	-17 ± 1
4	-21 ± 3	-19 ± 2	-19 ± 3	-24 ± 2	-19 ± 2	-17 ± 1
5	-22 ± 3	-18 ± 3	-16 ± 2	-21 ± 1	-19 ± 2	-17 ± 1
6	-21 ± 4	-18 ± 2	-17 ± 2	-24 ± 3	-18 ± 1	-21 ± 2

continued

Table C.7 - (continued)

	Diameter of sample (cm)					
	Carrot			Teething toast		
Subject	1.27	1.90	2.54	1.27	1.90	2.54
	Average amplitude (dB)[a]					
Chew 1						
1	-36 ± 2	-35 ± 3	-35 ± 2	-30 ± 1	-31 ± 3	-29 ± 2
2	-32 ± 2	-31 ± 3	-31 ± 2	-29 ± 3	-27 ± 3	-28 ± 3
3	-32 ± 4	-33 ± 3	-35 ± 3	-24 ± 2	-29 ± 3	-29 ± 3
4	-29 ± 3	-25 ± 3	-28 ± 3	-28 ± 3	-27 ± 2	-27 ± 2
5	-30 ± 3	-28 ± 3	-28 ± 4	-27 ± 3	-25 ± 2	-28 ± 2
6	-34 ± 3	-33 ± 2	-32 ± 5	-31 ± 3	-28 ± 3	-31 ± 2
Chew 2						
1	-34 ± 2	-34 ± 3	-33 ± 3	-33 ± 4	-30 ± 3	-32 ± 3
2	-32 ± 4	-30 ± 3	-29 ± 3	-31 ± 3	-27 ± 2	-28 ± 4
3	-32 ± 4	-31 ± 3	-34 ± 2	-28 ± 4	-31 ± 3	-29 ± 3
4	-30 ± 4	-29 ± 3	-29 ± 3	-32 ± 3	-33 ± 1	-29 ± 3
5	-32 ± 4	-31 ± 7	-30 ± 3	-29 ± 2	-30 ± 3	-28 ± 3
6	-34 ± 4	-31 ± 3	-32 ± 4	-33 ± 3	-27 ± 2	-31 ± 3

[a]Amplitude relative to full scale output of the sound spectrograph.

Table C.8 – Subject x sample diameter x food type interaction means ± standard deviations for frequency and amplitude[a] of formants 1-5 for sounds of the initial 2 chews of food samples (n=10 repetitions)

	Diameter of sample (cm)					
	Carrot			Teething toast		
Subject	1.27	1.90	2.54	1.27	1.90	2.54
	Formant 1: Frequency (Hz)					
Chew 1						
1	1580 ± 83	1492 ± 73	1384 ± 102	1424 ± 43	1436 ± 81	1368 ± 65
2	1748 ± 176	1332 ± 131	1382 ± 90	1580 ± 47	1408 ± 96	1360 ± 103
3	1432 ± 188	1316 ± 79	1216 ± 76	1340 ± 71	1300 ± 74	1212 ± 53
4	1312 ± 53	1276 ± 48	1224 ± 66	1332 ± 57	1216 ± 60	1080 ± 68
5	1538 ± 96	1374 ± 140	1380 ± 138	1612 ± 71	1504 ± 71	1500 ± 95
6	1280 ± 66	1172 ± 46	1218 ± 123	1324 ± 58	1084 ± 79	1104 ± 87
Chew 2						
1	1584 ± 89	1480 ± 60	1344 ± 102	1468 ± 84	1417 ± 96	1140 ± 60
2	1748 ± 82	1404 ± 154	1448 ± 128	1464 ± 89	1368 ± 65	1236 ± 140
3	1464 ± 146	1228 ± 116	1120 ± 88	1472 ± 73	1304 ± 104	1220 ± 104
4	1352 ± 106	1304 ± 100	1244 ± 76	1236 ± 85	1184 ± 71	1184 ± 91
5	1476 ± 97	1400 ± 112	1348 ± 158	1472 ± 75	1408 ± 53	1376 ± 63
6	1248 ± 160	1240 ± 80	1311 ± 98	1280 ± 68	1096 ± 100	1000 ± 110
	Formant 1: Amplitude (dB)					
Chew 1						
1	-22 ± 5	-18 ± 4	-13 ± 5	-14 ± 3	-17 ± 4	-19 ± 4
2	-21 ± 2	-16 ± 4	-14 ± 4	-13 ± 3	-15 ± 4	-17 ± 4
3	-15 ± 6	-16 ± 6	-14 ± 5	-10 ± 4	-14 ± 5	-14 ± 4
4	-15 ± 1	-13 ± 3	-13 ± 5	-9 ± 4	-8 ± 4	-8 ± 3
5	-15 ± 4	-20 ± 4	-16 ± 5	-12 ± 4	-10 ± 3	-13 ± 4
6	-13 ± 5	-16 ± 4	-14 ± 3	-13 ± 4	-9 ± 2	-17 ± 3
Chew 2						
1	-22 ± 4	-19 ± 5	-17 ± 5	-16 ± 6	-11 ± 3	-10 ± 3
2	-22 ± 6	-20 ± 6	-16 ± 5	-10 ± 3	-7 ± 1	-8 ± 3
3	-20 ± 5	-19 ± 5	-19 ± 5	-7 ± 4	-11 ± 4	-8 ± 4
4	-17 ± 3	-16 ± 4	-14 ± 6	-14 ± 3	-10 ± 2	-9 ± 3
5	-18 ± 6	-20 ± 5	-17 ± 5	-11 ± 4	-9 ± 3	-9 ± 4
6	-14 ± 3	-14 ± 5	-13 ± 2	-13 ± 4	-8 ± 5	-15 ± 6

continued

Table C.8 – (continued)

	Diameter of sample (cm)					
	Carrot			Teething toast		
Subject	1.27	1.90	2.54	1.27	1.90	2.54
	Formant 2: Frequency (Hz)					
Chew 1						
1	2384 ± 341	2456 ± 176	2348 ± 322	2536 ± 263	2380 ± 181	2436 ± 184
2	2540 ± 340	1912 ± 120	2151 ± 269	2188 ± 107	2296 ± 135	2784 ± 204
3	2248 ± 595	2008 ± 212	2048 ± 175	2792 ± 267	2640 ± 480	2800 ± 341
4	2092 ± 254	2404 ± 106	2348 ± 163	2188 ± 221	2420 ± 97	2336 ± 140
5	2316 ± 338	1920 ± 146	1924 ± 214	2652 ± 112	2056 ± 287	2600 ± 275
6	2080 ± 253	2116 ± 153	2089 ± 251	2104 ± 182	2376 ± 189	1880 ± 196
Chew 2						
1	2372 ± 324	2488 ± 194	2220 ± 144	2382 ± 190	2511 ± 215	2444 ± 179
2	2552 ± 188	1984 ± 215	2340 ± 368	2288 ± 207	2436 ± 109	2648 ± 191
3	2552 ± 939	1752 ± 149	1760 ± 150	2176 ± 282	1972 ± 139	2156 ± 452
4	2348 ± 242	2092 ± 135	2068 ± 299	2048 ± 237	2120 ± 136	2088 ± 384
5	2116 ± 291	2000 ± 263	1932 ± 299	2692 ± 50	1948 ± 144	2188 ± 259
6	2260 ± 228	2284 ± 316	2218 ± 298	2053 ± 267	1981 ± 348	2100 ± 277
	Formant 2: Amplitude (dB)					
Chew 1						
1	-28 ± 3	-28 ± 3	-24 ± 4	-29 ± 2	-29 ± 2	-29 ± 3
2	-23 ± 4	-14 ± 2	-14 ± 5	-22 ± 5	-24 ± 5	-24 ± 3
3	-16 ± 4	-14 ± 2	-18 ± 5	-20 ± 4	-27 ± 3	-25 ± 4
4	-16 ± 3	-12 ± 2	-15 ± 3	-17 ± 4	-14 ± 2	-15 ± 2
5	-20 ± 7	-13 ± 3	-14 ± 4	-25 ± 3	-14 ± 6	-20 ± 3
6	-21 ± 5	-25 ± 5	-23 ± 8	-27 ± 3	-22 ± 4	-24 ± 2
Chew 2						
1	-26 ± 6	-26 ± 4	-23 ± 4	-24 ± 4	-22 ± 4	-25 ± 3
2	-24 ± 3	-18 ± 5	-21 ± 5	-23 ± 2	-19 ± 2	-21 ± 4
3	-22 ± 8	-16 ± 4	-17 ± 4	-18 ± 15	-15 ± 3	-15 ± 8
4	-24 ± 4	-21 ± 4	-18 ± 5	-23 ± 3	-18 ± 2	-17 ± 2
5	-23 ± 4	-17 ± 4	-16 ± 6	-29 ± 3	-15 ± 4	-20 ± 4
6	-24 ± 7	-25 ± 4	-25 ± 4	-26 ± 4	-22 ± 5	-25 ± 2

continued

Table C.8 – (continued)

	Diameter of sample (cm)					
	Carrot			Teething toast		
Subject	1.27	1.90	2.54	1.27	1.90	2.54
	Formant 3: Frequency (Hz)					
Chew 1						
1	3198 ± 145	3336 ± 146	3228 ± 252	3328 ± 197	3296 ± 223	3264 ± 141
2	3624 ± 435	2852 ± 261	3107 ± 375	3240 ± 224	3212 ± 331	3392 ± 176
3	4012 ± 383	3700 ± 188	3088 ± 424	3860 ± 115	3672 ± 594	3620 ± 284
4	3260 ± 127	3256 ± 69	2996 ± 160	3116 ± 188	3280 ± 50	3120 ± 110
5	3098 ± 337	3184 ± 216	2980 ± 322	2652 ± 112	2920 ± 327	2600 ± 275
6	3418 ± 179	3144 ± 156	3031 ± 280	2900 ± 125	3140 ± 287	2884 ± 177
Chew 2						
1	3204 ± 179	3312 ± 176	3252 ± 293	3182 ± 208	3431 ± 264	3016 ± 165
2	3664 ± 320	2960 ± 302	3252 ± 368	3272 ± 302	3404 ± 264	3664 ± 144
3	4112 ± 820	3672 ± 178	3112 ± 288	3548 ± 302	3660 ± 158	3632 ± 92
4	3056 ± 192	2920 ± 151	2960 ± 376	2916 ± 143	2936 ± 261	2924 ± 187
5	3156 ± 350	3272 ± 177	3060 ± 261	3804 ± 163	2896 ± 204	3716 ± 243
6	3400 ± 379	3218 ± 337	3124 ± 377	2856 ± 354	2880 ± 194	2808 ± 49
	Formant 3: Amplitude (dB)					
Chew 1						
1	-22 ± 6	-20 ± 4	-18 ± 6	-24 ± 4	-23 ± 3	-22 ± 3
2	-25 ± 4	-25 ± 3	-22 ± 3	-25 ± 3	-24 ± 3	-25 ± 3
3	-24 ± 3	-22 ± 4	-24 ± 4	-21 ± 4	-23 ± 3	-22 ± 4
4	-18 ± 4	-17 ± 3	-17 ± 4	-17 ± 4	-15 ± 3	-14 ± 2
5	-21 ± 5	-28 ± 3	-24 ± 4	-23 ± 3	-23 ± 3	-24 ± 3
6	-21 ± 4	-22 ± 5	-22 ± 3	-26 ± 5	-18 ± 5	-25 ± 3
Chew 2						
1	-24 + 4	-23 ± 3	-21 ± 3	-25 ± 5	-21 ± 3	-24 ± 3
2	-28 + 3	-24 ± 3	-23 ± 6	-26 ± 4	-24 ± 1	-21 ± 2
3	-28 + 4	-23 ± 4	-25 ± 3	-20 ± 5	-22 ± 3	-19 ± 3
4	-22 + 5	-19 ± 5	-19 ± 4	-21 ± 4	-18 ± 2	-15 ± 4
5	-25 + 4	-23 ± 3	-25 ± 6	-24 ± 5	-27 ± 3	-24 ± 3
6	-25 ± 3	-22 ± 4	-22 ± 3	-27 ± 3	-20 ± 3	-25 ± 2

continued

Table C.8 – (continued)

	Diameter of sample (cm)					
	Carrot			Teething toast		
Subject	1.27	1.90	2.54	1.27	1.90	2.54
	Formant 4: Frequency (Hz)					
Chew 1						
1	3862 ± 186	4044 ± 245	4000 ± 236	4036 ± 173	3964 ± 139	3816 ± 110
2	4384 ± 279	3912 ± 371	3947 ± 434	4068 ± 151	4060 ± 206	4204 ± 188
3	4800 ± 679	4668 ± 511	3884 ± 356	4868 ± 300	4616 ± 669	4533 ± 398
4	4020 ± 377	4020 ± 310	3908 ± 393	3952 ± 392	4060 ± 236	3832 ± 206
5	3975 ± 323	4267 ± 147	4136 ± 269	4568 ± 275	4076 ± 358	4416 ± 218
6	4351 ± 352	3944 ± 235	3627 ± 214	3624 ± 382	4052 ± 280	3716 ± 307
Chew 2						
1	3948 ± 224	3964 ± 228	4016 ± 277	3783 ± 219	4031 ± 188	3820 ± 149
2	4410 ± 409	3844 ± 253	4060 ± 312	4084 ± 124	4088 ± 138	4368 ± 218
3	5289 ± 828	4848 ± 587	4388 ± 922	4604 ± 683	4616 ± 618	4796 ± 460
4	3840 ± 350	3880 ± 482	3744 ± 431	3818 ± 308	3804 ± 456	3884 ± 341
5	3971 ± 392	4108 ± 201	4012 ± 239	4452 ± 247	3844 ± 234	4364 ± 246
6	4200 ± 314	4116 ± 200	3851 ± 271	3665 ± 339	3864 ± 272	3756 ± 158
	Formant 4: Amplitude (dB)					
Chew 1						
1	-22 ± 3	-19 ± 2	-20 ± 3	-24 ± 3	-23 ± 2	-22 ± 3
2	-24 ± 3	-23 ± 4	-23 ± 4	-20 ± 3	-21 ± 5	-23 ± 2
3	-26 ± 4	-26 ± 3	-22 ± 4	-26 ± 3	-26 ± 4	-25 ± 2
4	-24 ± 4	-22 ± 4	-23 ± 5	-22 ± 4	-21 ± 3	-18 ± 2
5	-23 ± 2	-24 ± 4	-23 ± 5	-26 ± 4	-21 ± 4	-24 ± 4
6	-27 ± 4	-25 ± 3	-21 ± 2	-27 ± 2	-23 ± 5	-23 ± 3
Chew 2						
1	-26 ± 3	-22 ± 2	-21 ± 3	-28 ± 4	-21 ± 3	-22 ± 2
2	-26 ± 4	-24 ± 3	-22 ± 3	-23 ± 5	-19 ± 1	-22 ± 2
3	-30 ± 6	-27 ± 5	-26 ± 4	-24 ± 3	-26 ± 3	-24 ± 4
4	-26 ± 3	-24 ± 4	-23 ± 4	-26 ± 4	-23 ± 4	-22 ± 3
5	-22 ± 2	-21 ± 4	-20 ± 3	-23 ± 3	-25 ± 3	-23 ± 3
6	-23 ± 3	-24 ± 4	-21 ± 3	-26 ± 2	-23 ± 4	-25 ± 4

continued

Table C.8 – (continued)

	Diameter of sample (cm)					
	Carrot			Teething toast		
Subject	1.27	1.90	2.54	1.27	1.90	2.54
	Formant 5: Frequency (Hz)					
Chew 1						
1	4618 ± 390	4832 ± 395	4696 ± 340	4720 ± 384	5098 ± 158	4848 ± 176
2	5491 ± 576	4728 ± 229	4585 ± 452	5148 ± 160	4982 ± 203	5018 ± 249
3	5698 ± 616	5670 ± 328	4631 ± 366	5844 ± 448	5924 ± 913	6018 ± 597
4	4884 ± 197	4846 ± 271	4848 ± 360	4932 ± 228	4772 ± 190	4636 ± 118
5	4795 ± 231	5155 ± 155	5136 ± 318	5227 ± 159	4972 ± 266	5088 ± 281
6	5215 ± 329	4942 ± 480	4670 ± 352	4355 ± 382	4764 ± 167	4560 ± 256
Chew 2						
1	4742 ± 394	4636 ± 304	4831 ± 317	4672 ± 535	5040 ± 268	4377 ± 1373
2	5144 ± 338	4640 ± 193	5013 ± 42	5115 ± 317	5031 ± 238	5080 ± 328
3	6125 ± 493	5615 ± 483	5509 ± 757	5982 ± 554	5893 ± 620	6020 ± 378
4	4800 ± 144	4840 ± 330	4760 ± 290	5025 ± 158	4780 ± 280	4544 ± 203
	4816 ± 450	4996 ± 308	5200 ± 272	5071 ± 163	4776 ± 228	5016 ± 214
6	4949 ± 261	4924 ± 312	4756 ± 320	4480 ± 622	4596 ± 314	4689 ± 278
	Formant 5: Amplitude (dB)					
Chew 1						
1	-24 ± 3	-25 ± 4	-21 ± 5	-29 ± 3	-27 ± 2	-25 ± 3
2	-24 ± 5	-24 ± 4	-22 ± 5	-28 ± 2	-25 ± 3	-25 ± 4
3	-26 ± 3	-27 ± 2	-24 ± 5	-25 ± 3	-28 ± 3	-27 ± 4
4	-22 ± 3	-24 ± 3	-26 ± 3	-25 ± 3	-22 ± 3	-18 ± 3
5	-24 ± 3	-23 ± 2	-26 ± 4	-25 ± 2	-23 ± 2	-25 ± 2
6	-27 ± 4	-26 ± 4	-21 ± 3	-28 ± 2	-25 ± 2	-26 ± 2
Chew 2						
1	-27 ± 3	-23 ± 4	-26 ± 3	-26 ± 2	-22 ± 2	-26 ± 3
2	-25 ± 3	-25 ± 4	-26 ± 4	-29 ± 2	-24 ± 4	-25 ± 2
3	-28 ± 3	-29 ± 2	-28 ± 4	-24 ± 4	-26 ± 3	-24 ± 2
4	-26 ± 4	-26 ± 3	-23 ± 2	-28 ± 3	-26 ± 2	-23 ± 4
5	-26 ± 2	-24 ± 4	-25 ± 4	-25 ± 2	-26 ± 4	-26 ± 3
6	-24 ± 4	-25 ± 2	-26 ± 3	-26 ± 1	-26 ± 3	-29 ± 3

[a]Amplitude relative to that of a calibration tone (1000 Hz, 80 dB).

Table C.9 – Subject x sample diameter x food type interaction means ± standard deviations for durations (msec) of sounds for the initial 2 chews of food samples (n=10 repetitions)

	Diameter of sample (cm)					
	Carrot			Teething toast		
Subject	1.27	1.90	2.54	1.27	1.90	2.54
Chew 1						
1	317 ± 59	361 ± 56	380 ± 61	395 ± 113	459 ± 79	484 ± 149
2	330 ± 55	328 ± 53	361 ± 52	347 ± 74	327 ± 69	387 ± 71
3	273 ± 73	320 ± 71	532 ± 87	277 ± 49	491 ± 178	463 ± 135
4	225 ± 41	210 ± 48	313 ± 79	254 ± 55	254 ± 71	281 ± 50
5	292 ± 51	300 ± 40	407 ± 70	363 ± 96	318 ± 117	372 ± 48
6	499 ± 100	451 ± 114	444 ± 120	480 ± 152	382 ± 63	689 ± 226
Chew 2						
1	247 ± 29	308 ± 29	311 ± 80	218 ± 21	302 ± 51	302 ± 46
2	215 ± 31	264 ± 34	278 ± 28	171 ± 13	199 ± 14	232 ± 41
3	191 ± 52	263 ± 21	333 ± 67	192 ± 35	278 ± 63	295 ± 69
4	186 ± 35	202 ± 38	252 ± 32	190 ± 32	232 ± 44	222 ± 25
5	250 ± 36	256 ± 38	313 ± 62	320 ± 46	316 ± 45	362 ± 44
6	332 ± 61	357 ± 71	427 ± 76	367 ± 60	329 ± 82	347 ± 68
Onset of chew 1 to onset of chew 2						
1	720 ± 52	807 ± 96	846 ± 141	705 ± 137	782 ± 120	848 ± 200
2	675 ± 70	783 ± 92	725 ± 75	621 ± 74	642 ± 73	727 ± 70
3	659 ± 93	711 ± 107	945 ± 148	655 ± 65	971 ± 229	867 ± 150
4	511 ± 41	592 ± 166	729 ± 186	497 ± 60	492 ± 73	590 ± 72
5	705 ± 122	642 ± 62	852 ± 149	743 ± 118	768 ± 104	758 ± 95
6	1250 ± 325	1000 ± 166	885 ± 299	1040 ± 285	854 ± 122	1110 ± 233
End of chew 1 to onset of chew 2						
1	430 ± 42	446 ± 78	478 ± 92	310 ± 30	322 ± 58	364 ± 61
2	346 ± 40	456 ± 93	364 ± 68	274 ± 26	316 ± 27	341 ± 27
3	386 ± 36	392 ± 70	413 ± 115	378 ± 57	480 ± 87	404 ± 54
4	280 ± 46	382 ± 171	416 ± 131	242 ± 57	238 ± 37	309 ± 50
5	387 ± 97	342 ± 46	445 ± 105	380 ± 50	450 ± 81	386 ± 71
6	660 ± 252	534 ± 117	440 ± 197	556 ± 160	455 ± 91	426 ± 91
Onset of chew 1 to end of chew 2						
1	966 ± 63	1110 ± 107	1160 ± 161	923 ± 147	1110 ± 168	1150 ± 231
2	889 ± 85	1050 ± 86	1000 ± 75	792 ± 72	841 ± 73	960 ± 92
3	850 ± 125	975 ± 115	1280 ± 194	847 ± 54	1250 ± 258	1120 ± 135
4	697 ± 54	794 ± 174	981 ± 207	687 ± 69	724 ± 90	811 ± 81
5	948 ± 105	898 ± 73	1170 ± 153	1050 ± 125	1080 ± 120	1120 ± 97
6	1590 ± 306	1360 ± 200	1310 ± 319	1400 ± 278	1180 ± 121	1460 ± 204

Table C.10 – Subject x sample diameter x food type interaction means ± standard deviations for oscilloscopic parameters for sounds of the initial 2 chews of food samples (n=10 repetitions)

	Diameter of sample (cm)					
	Carrot			Teething toast		
Subject	1.27	1.90	2.54	1.27	1.90	2.54
	Time (msec)					
Chew 1						
1	244 ± 82	273 ± 57	340 ± 60	381 ± 102	444 ± 63	498 ± 116
2	264 ± 31	299 ± 62	339 ± 61	317 ± 51	303 ± 63	375 ± 80
3	224 ± 33	273 ± 80	461 ± 96	285 ± 42	430 ± 119	387 ± 100
4	212 ± 34	201 ± 47	270 ± 61	216 ± 40	245 ± 69	271 ± 60
5	284 ± 55	296 ± 43	387 ± 60	334 ± 68	311 ± 54	366 ± 46
6	437 ± 83	398 ± 79	334 ± 137	448 ± 145	362 ± 76	486 ± 168
Chew 2						
1	229 ± 34	275 ± 63	297 ± 87	187 ± 24	281 ± 35	335 ± 63
2	202 ± 24	246 ± 37	271 ± 33	169 ± 18	198 ± 17	206 ± 37
3	180 ± 31	237 ± 32	308 ± 81	173 ± 35	260 ± 67	264 ± 50
4	169 ± 30	179 ± 21	233 ± 44	162 ± 28	240 ± 32	227 ± 35
5	262 ± 23	248 ± 39	303 ± 45	296 ± 43	346 ± 42	381 ± 51
6	306 ± 71	330 ± 72	314 ± 105	294 ± 50	303 ± 78	322 ± 108
	Peak time (msec)					
Chew 1						
1	108 ± 56	105 ± 55	185 ± 60	182 ± 65	245 ± 78	265 ± 153
2	88 ± 29	99 ± 58	103 ± 67	130 ± 55	123 ± 69	218 ± 60
3	60 ± 22	76 ± 49	190 ± 73	103 ± 57	214 ± 58	196 ± 85
4	78 ± 8	77 ± 20	90 ± 35	61 ± 36	100 ± 35	99 ± 42
5	109 ± 56	134 ± 45	187 ± 48	144 ± 57	109 ± 48	179 ± 34
6	178 ± 82	140 ± 67	93 ± 74	249 ± 92	115 ± 57	115 ± 35
Chew 2						
1	92 ± 33	104 ± 35	148 ± 67	71 ± 23	84 ± 18	117 ± 50
2	94 ± 50	95 ± 46	119 ± 35	45 ± 23	59 ± 24	77 ± 20
3	84 ± 44	71 ± 39	136 ± 74	64 ± 22	87 ± 43	112 ± 43
4	74 ± 25	68 ± 30	109 ± 35	61 ± 34	114 ± 35	102 ± 44
5	102 ± 63	130 ± 36	303 ± 45	163 ± 55	159 ± 42	139 ± 52
6	114 ± 84	149 ± 65	114 ± 79	153 ± 61	101 ± 74	115 ± 72

continued

Table C.10 – (continued)

	Diameter of sample (cm)					
	Carrot			Teething toast		
Subject	1.27	1.90	2.54	1.27	1.90	2.54
	Peak amplitude (dB)[a]					
Chew 1						
1	-3 ± 2	-2 ± 1	-2 ± 1	-2 ± 1	-2 ± 1	-3 ± 1
2	-2 ± 1	-1 ± 1	0 ± 1	-2 ± 2	-2 ± 2	-2 ± 1
3	-1 ± 1	0 ± 1	0 ± 1	0 ± 1	0 ± 1	0 ± 0
4	-1 ± 1	0 ± 0	0 ± 0	-2 ± 1	0 ± 1	0 ± 0
5	-1 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 1	0 ± 1
6	0 ± 0	-1 ± 1	0 ± 1	0 ± 0	0 ± 1	-1 ± 1
Chew 2						
1	-3 ± 1	-4 ± 2	-3 ± 2	-7 ± 4	-3 ± 1	-3 ± 2
2	-5 ± 3	-1 ± 1	-1 ± 1	-4 ± 2	-2 ± 2	-2 ± 1
3	-2 ± 2	0 ± 1	-2 ± 1	-1 ± 1	-3 ± 2	0 ± 0
4	-4 ± 3	-1 ± 0	-2 ± 2	-5 ± 2	-2 ± 2	-1 ± 2
5	-2 ± 2	-1 ± 1	0 ± 1	-2 ± 1	-1 ± 2	0 ± 0
6	-2 ± 2	-1 ± 1	0 ± 1	-3 ± 2	0 ± 1	-2 ± 1

[a]Amplitude relative to that of a calibration tone (1000 Hz, 80 dB).

VITA

Denise Brochetti was born in Brookville, Pennsylvania, on November 14, 1953. She attended public schools in Clarion, Pennsylvania, and was graduated from Clarion Area High School. She entered college in 1971 at Indiana University of Pennsylvania. In 1973 she transferred to Columbia Hospital School of Nursing, Pittsburgh, Pennsylvania, where she received a Diploma in Nursing in 1976. She then moved to Washington, DC., where she was employed at George Washington University Medical Center as a registered nurse. In 1978 she assumed responsibilities of nursing coordinator at Women's Medical Center, Washington, DC.

In 1981 Denise entered the experimental foods program at The University of Maryland, College Park. In 1984 requirements were met for a Bachelor of Science degree in Food, Nutrition, and Institution Administration. Throughout her undergraduate studies, she was employed part time as a registered nurse at Columbia Hospital for Women, Washington, DC.

In 1985 she began graduate studies at The University of Tennessee, Knoxville, where she held a United States Department of Agriculture National Needs Fellowship. In 1987 she received a Master of Science degree in Food Science. Following graduation, she continued studies at The University of Tennessee, Knoxville, and was employed as a research assistant in the Agricultural Experiment Station. In 1991 she received a Doctor of Philosophy degree in Food Technology and Science.

Denise is a member of the Institute of Food Technologists, American Association of Cereal Chemists, and Phi Kappa Phi, Kappa Omicron Nu, and Gamma Sigma Delta honor societies.