FOOD SOUNDS: SENSORY, ACOUSTIC, AND MECHANICAL ANALYSIS OF TWO SNACK FOODS

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ABSTRACT

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The effect of alteration of water activity levels of two dry snack foods on participants' ratings of sensory crispness, loudness, pitch, and pleasantness, and the acoustic measures of amplitude (in volts) and peak frequency (Hz) of recorded food bite sounds were investigated. Increased water activity resulted in decreased sensory ratings for both products, confirming previous studies. Measurements of acoustic amplitudes and frequencies indicated that for tortilla chips sound amplitudes tended to increase with increased water activity while Melba toast sound amplitudes decreased. While peak frequency analysis revealed that tortilla chip bite sounds were higher than those of the Melba toast, no differences were found across a_w for either product. Correlations of sensory and acoustic parameters showed that, for each product, the strongest relationship was between loudness and crispness. However, different trends were noted in the correlations of individual products and led to the suggestion that participants may have rated the two products differently. Mechanical force-deformation analysis was performed and informally compared to the pattern of sensory and acoustic results where peak force (N) was seen to increase as sound amplitude increased. Future research into the mechanical parameters of dry products and the role of vibro-tactile sensations is recommended.

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INTRODUCTION

The relationship between food mastication sounds and food acceptability is widely recognized. It is embodied in the consumers' approval of low moisture (i.e., dry) crisp food products like potato chips and their rejection of these same products when they have greater moisture content. Whereas early research into food mastication sounds focussed almost exclusively on sensory crispness (e.g., Christensen &Vickers, 1981; Vickers & Bourne, 1976a) and its relation to mechanical parameters (Edmister &Vickers, 1985; Katz & Labuza, 1981; Vickers, 1988), more recent investigations focussed on the associations between objective acoustic dimensions of mastication sounds (e.g., amplitude and frequency), subjective sensory crispness (discernible from sound produced by biting a product), and pleasantness (Bisschop, 1995; Boehnke, 1996). The general finding emerging from such research was that increasing the moisture content of certain dry-crisp products resulted in participant bite ratings characterizing the products as less crisp (Sauvageot & Blond, 1991; Seymour & Hamann, 1988). Acoustically, the more moist products were judged to be less loud (Kapur, 1971; Vickers, 1985), of lower pitch (Boehnke, 1995; Lee, Deibel, Glembin, & Munday, 1988), and less pleasant (Bisschop, 1995; Boehnke, 1996).

A point of contention with respect to food sound studies is that, rather than using formal operational definitions, researchers often relied on participants' implicit knowledge of the sensation of crispness. Ironically, such an open-ended approach seems to have facilitated inconsistencies in researchers' conclusions. While there may be a consensus on subjective aspects of crispness sensation, researchers are yet to find a common set of objective acoustic parameters to define the sensation of crispness.

The current study will monitor consumer judgements of food acceptance as a function of changes in crispness, here defined as a function of water activity (a_w: a physicochemical property of water ranging between values of zero and one, with higher values indicating higher moisture content). The addition of water to a dry food product alters its physical structure and facilitates a loss of mechanical strength that can be measured instrumentally. Since such structural changes are believed to become manifest under the forces of mastication, crispness and pleasantness judgments are considered amenable to psychophysical investigations. Consequently, such mechanical changes will be investigated through subjective sensory judgments and correlated both with objective acoustic parameters and physical measurements of food structure. Thus, the study is an attempt to understand the crispness sensation qua pleasantness as derived from the mechanical and acoustic properties of the particular products to be tested. What follows is an outline of the scientific progress in food sounds leading to the current understanding of food crispness and how such research contributed to the present study.

Food Texture

The role of food texture in North American consumer behaviour was identified when it was shown that texture was not only a discernible characteristic of food, often surpassing flavour in importance (Szczesniak, 1971; Szczesniak & Kahn, 1971; Szczesniak& Kleyn, 1963) but that consumers had implicit knowledge of textural descriptors such as crispness and used them in similar situations. Comparable observations were made in France (Dacremont, 1995) and Japan (Yoshikawa, Nishimaru,

& Yoshida, 1970a,b,c). The research that followed led to the general definition of texture as "the sensory manifestation of the structure of the food and the manner in which this structure reacts to the applied forces, the specific senses involved being vision, kinesthetics and hearing" (Szczesniak, 1991, p.77). Besides acknowledging the multifaceted sensory nature of texture and its links to structure, the definition highlights the need for separate, specific investigations into material structure and sensory systems.

Early Work on Food Sounds

After conducting extensive spectrographic analysis of food sounds, Drake (1963; 1965) argued that mastication involved an acoustic dimension and that physical measurements of crushing sounds should be correlated with consumers' sensory data. Vickers and Bourne investigated the viability of Drake's claim and did a comprehensive review of the literature (1976a) that culminated in the postulation of a Psychoacoustical Theory of Crispness (1976b). Crispness was hypothesized to be primarily an auditory sensation, by which the crushing of cellular material resulted in the rupture of cell walls with corresponding sound emission. However, unable to account for crispness judgments made without acoustic signals (Christensen & Vickers, 1981; Vickers & Christensen, 1980) the theory was revised and crispness was regarded as a vibratory sensation. The assertion that crispness involved the auditory and oral tactile senses formed the basis for much of subsequent research into food sounds.

Effects of Moisture Level

Preliminary studies revealed that many consumers equate crispness with freshness, as reflected in consumers' acceptance of fresh, firm, crisp vegetables with high water content (i.e., high a_w), and the rejection of older, limp, wilted vegetables that have a reduced water content (i.e., lower a_w.). The notion that fresh and crisp were synonymous, along with Drake (1963) and Kapur's (1971) early work on food sounds, served as preliminary evidence that water content was related to acoustic and sensory measures subsequently linked to crispness. This prompted investigators to address how changes in a product's a_w could affect its perceived crispness.

Katz and Labuza (1981) found that as the a_w of dry-crisp snack foods increased, sensory ratings of crispness decreased. They postulated that increased water availability affected a product's water binding behaviour, thereby allowing its macromolecules to slip past one another during eating. It was beleived that observers were able to perceive such structural changes and, accordingly, to judge products as less crisp. Added moisture resulted in reduced cavity wall ruptures which led to less sound production and reduced crispness judgments as expressed in the psychoacoustical theory.

Similarly, Sauvageot and Blond (1991) created ten equal-interval a_w values of normally dry, ready to eat breakfast cereals, and found that sensory crispness ratings decreased sigmoidally as a_w level increased. Interestingly, the curve was relatively flat for a_w values between 0.0 and 0.5, but dropped sharply beyond $a_w = 0.5$. As a result, this value was regarded as the critical water activity level (a_c)(i.e., the moisture level) at which subjects could detect a change in water binding behaviour, reported as a decrease in sensory crispness. Again, these results agree with the psychoacoustical theory and allow the inference that the crispness of other dry foods (e.g., crackers, potato chips) would also show inverse relations between crispness judgments and a_w.

Eating Method

An important consideration for the study of food mastication sounds is the method by which the food is broken down in the mouth, since sound waves are transmitted through both air and bone conduction toward the inner ear. However, the proportions of air and bone conducted sounds that reach the ears are different when food is bitten with the front teeth or chewed with the molars. To investigate the relative contributions of air and bone sound conduction to crispness judgments, Dacremont, Colas, and Sauvageot (1991) recorded both components of each judge's bite and chew sounds of crisp wafers. Using the recordings of their own bite and chew sounds, each judge then used an electronic mixing board to adjust the ratio of air and bone conducted sounds to imitate the crispness sensation. The authors analysed the remixed sounds and reported that air and bone conduction have similar importance when food is bitten but not when it is chewed. Previous studies (e.g., Christensen & Vickers, 1981; Sherman & Deghaidy, 1978; Vickers & Christensen, 1980) report that in making crispness and loudness judgments the bulk of the sensory information used by subjects was contained in the initial fracture of the food by the incisors. Such conclusions are consistent with the Haas phenomenon (also known as the precedence effect and the principle of first wavefront): within a particular time-frame, an early-arriving signal will dominate over a later-arriving signal in determining what we hear (Gardner, 1968). Consequently, Bisschop (1995) and Boehnke (1996) had participants hold a food sample with tweezers and bite the sample once with the front teeth, keeping the lips open. This method enabled them to report the first unequivocal finding that participants can scale the crispness, loudness, and pleasantness of the resultant sounds. Boehnke additionally mounted a microphone on the tweezers and found this method to be successful for obtaining clear, reliable recordings of the bite sounds.

Psychophysical Scaling

Previous attempts to scale crispness as a function of moisture content often relied on the ratio scaling technique of modulus-free magnitude estimation (e.g., Christensen & Vickers, 1981) whereby participants judged the crispness of a set of stimuli by assigning numbers thought to reflect differences in crispness. Other scaling attempts (Vickers, 1983a; Vickers & Christensen, 1980) involved the use of category scales, whereby responses were assumed to fall along an interval scale ranging from "very slightly crisp" to "extremely crisp", with participants marking a point on a line corresponding to crispness.

Vickers (1983b) compared the two methods in a study of the hedonic quality of crisp vegetable and snack food sounds and found them to produce very similar results ($r = .99$). Bisschop (1995) and Boehnke (1996) had participants use the paired-comparison method (with standard) combined with interval scale judgments and observed high correlations between the scaled acoustic dimensions of crispness, loudness, pitch, and pleasantness. The advantage of the paired-comparison technique, unlike that of modulus-free magnitude estimation, was the ease of data manipulation. Since participants' product ratings were anchored along a line scale ranging from 0-10 (unlike the virtually limitless number range used in magnitude estimation) data did not require normalization.

Acoustic Analysis

In preliminary acoustic studies Drake (1963, 1965) and Kapur (1971) fed tape-recorded food crushing sounds through audio spectrometers to produce time averaged amplitude-frequency traces. However, this analysis was limited to broad frequency bands and thus offered poor overall sound wave resolution. Vickers and Bourne (1976b) created amplitude-frequency traces of recorded food sound at 10 ms intervals using a real-time spectrum analyser that displayed only frequencies below 10.0 kHz. By so doing, the authors made the assumption that the effects of any frequencies above this value were negligible.

Seymour and Hamann (1984; 1988) were the first to use Fast Fourier Transformations (FFT) to provide amplitudes for each frequency in a complex food sound. While FFT allowed greater precision, the sampling rate of their computer system limited analysis to frequencies in the range 0-3.3 kHz. Lee et al. (1988) also did FFTs on a series of chews of fresh and stale potato chip and tortilla chip samples and witnessed frequencies covering the range of 0-20 kHz. Sound data from each sample were divided into twenty equal segments, 1.0 kHz in width, with all spectra averaged to produce a single amplitude-frequency spectrum averaged over the full time-course of the sound. They thus reported no possible amplitude-frequency variations within the full time-course of the sound.

Boehnke (1996) used Wave for Windows (Turtle Beach software) to do FFTs of cracker bite sounds to separate amplitude-frequency traces for each instant in time (ms) to see if this methodology might provide more accurate data in future studies. The time slices were aligned to produce a three-dimensional representation of the bite sound and allowed informal inspection of amplitude-frequency changes over the entire sound file, and appeared to provide a viable approach to sound analysis. While Boehnke's recording equipment allowed for single channel recordings of 8 bits per second at 44.1 kHz (tape quality) with frequencies between 0-20.0 kHz, the time resolution was not as fine as the anticipated one millisecond. A faster computer could capture 16 bits per second, resulting in CD quality recordings and would presumably allow investigation of each millisecond in time.

Amplitude and Loudness of Mastication Sounds

Drake (1963) was the first to report formally that sounds from crisp foods differed from non crisp food sounds. Specifically, Drake reported that the crisper foods were louder, with loudness varying subjectively with sound amplitude. Kapur (1971) and Vickers and Bourne (1976b) reported similar findings using wafers and saltines respectively. The sounds from the more crisp samples of each product were reported to have up to double the loudness of that produced from samples with higher moisture. Such evidence associating both crispness and sensory loudness with moisture level led to the proposition that crispness and loudness should be correlated; a finding confirmed by a variety of researchers (e.g., Bisschop, 1995; Boehnke, 1996; Christensen & Vickers, 1981; Vickers, 1985; Vickers & Wasserman, 1979).

Having established a relationship between crispness and loudness, it became necessary to characterize food sounds in terms of their acoustical parameters. To do so Edmister and Vickers (1985) and Vickers (1987) used dry snack foods in attempts to correlate participants' crispness judgments with three acoustic parameters: number of amplitude peaks or occurrences, mean voltage height of all the peaks, and duration of the sound in seconds. However, the findings of the studies were inconsistent with one another. Seymour & Hamann (1988) found that both crispness judgments and mean sound wave pressure (MP) decreased as the a_w of crisp foods increased. Later, Lee, Schweitzer, Morgan, and Shepherd (1990) reported correlations no smaller than $r = .877$ between crispness judgments of fresh and stale potato and tortilla chips and peak sound levels (dB) produced during chewing. However, no differences were found between fresh and stale samples for either product.

Boehnke (1996) used digitized bite sounds of four moisture levels of three dry snack foods in an attempt to relate crispness to sound amplitude, represented by the root mean square (rms) voltage. The amplitude was reported to have differed both across and within products and across moisture levels; a similar pattern of differences was observed for the highly correlated ($r = .99$) crispness (i.e., moisture content) and sensory loudness judgments.

Although generally acceptable amplitude parameters are yet to be identified, previous research does offer sufficient support for the contention that crispness is related to sensory loudness and sound amplitude. However, it is unlikely that amplitude differences alone are responsible for all differences in perceptions of crispness.

Frequency and Pitch of Mastication Sounds

While the association between crispness and loudness is well established, few studies have investigated the role of pitch in crispness. Pitch subjectively varies most readily with frequency changes, and many people are unaware of its nuances. Thus before participants can be asked to rate food sounds using this attribute, they should show an appreciation of it. This can be accomplished by having participants practise pitch discrimination on a series on tones differing in frequency.

In the first formal attempts to determine whether food crispness might be characterized by higher-pitched sounds, Vickers probed judges' abilities to rate the pitch of those foods generally considered more crisp than crunchy and those generally considered more crunchy than crisp. The results showed that participants could judge bitten and chewed crisp foods as higher in pitch than those of crunchy foods (Vickers, 1984) and less crisp foods (Vickers, 1985), thereby supporting her assumption.

As human perception of sound frequency is most frequently confounded with sound amplitude, any specific investigation of pitch must necessarily consider loudness of characteristic frequencies. Lee et al. (1988) reported a relationship between crispness and frequency-amplitude after they found the first chew of a fresh chip (potato or tortilla, with low a_w) to produce large amplitudes in the 9.0-12.0 kHz frequency range. The first chew of a stale chip (higher a_w) failed to produce appreciable acoustic energy in this frequency range, instead the high amplitude peaks were observed at lower frequencies. In addition, these researchers examined amplitude-frequency traces of the mastication sound and reported the first chew of fresh, but not stale, samples to be characterized by a "double-hump" pattern with amplitude peaks at 3.0-4.0 kHz and 6.0 kHz. In part due to these observations, they concluded that the most relevant information regarding crispness was contained in the first mastication of the product; a finding similar to that reported by Vickers and Christensen (1980).

Although the Lee et al. (1988) findings have not been replicated, they offer preliminary evidence for the assertion that distinct frequency ranges associated with high amplitudes may be related to moisture level, and by definition, crispness. Moreover, if the bimodal or "double-hump" pattern can be shown for other products it may provide clues into the distinguishing characteristics of crispness.

Hedonic Aspects of Food Sounds

While it seems generally accepted that food texture and crispness are linked to the appreciation of food, it is less clear how this arises. Vickers (1983a) first investigated the pleasantness of food mastication sounds and reported that of nine auditory qualities crispness was the most closely associated with pleasantness ($r = .36$). However, of the sixteen sounds that participants' judged, only two individual food sounds displayed positive correlations between crisp and pleasant. Loudness was positively (though not significantly) correlated with pleasantness. The association of loudness and pleasantness is interesting because of Vickers' previous reports, noted earlier, that loudness and crispness were highly correlated. Consequently, Vickers concluded that different sound attributes might vary in their relationship with pleasantness depending on the food sound considered.

Bisschop (1995) used a paired-comparison method to investigate the pleasantness of dry snack food mastication sounds and reported that participants' judgments of pleasantness and crispness were highly correlated ($r = .79$) as were pleasantness and loudness judgments ($r = .83$). Boehnke (1996) used the same scaling technique and two of the same food products and found even higher correlations of pleasantness with crispness ($r = .98$) and loudness ($r = .96$). Boehnke also had a subset of participants judge the pitch rather than the loudness of the food sounds and noted that pleasantness was highly correlated with pitch ($r = .95$). While the results clearly showed the judges' ability to scale food pleasantness as a function of crispness (i.e., moisture content), the samples used in each study were steamed, and thus, not rigorously controlled. Furthermore, the moist samples were obviously discernible from the dry samples and allowed the strong relationships reported. Tighter control on sample preparation methods and finer differences between moisture levels should probe consumers' abilities to scale pleasantness when differences between adjacent moisture levels are more modest.

Mechanical Measures of Food Structure

Many attempts to quantify food crispness have involved rheological testing methods (e.g., Andersson, Drake, Granquist, Halldin, Johansson, Pangborn, & Åkesson, 1973; Sauvageot & Blond, 1991; Vickers, 1988), whereby investigations are focussed on food material structure when under stress, such as occurs during the mastication process. For instance, Katz and Labuza (1981) found the initial slope of the force-deformation curve (i.e., apparent stiffness) and peak force (N) at fracture, from a snap test, to be good indicators of sensory crispness and product acceptability. Vickers (1987) subsequently reported, in a study of potato chips sensory crispness, that the combination of instrumental mechanical and acoustic parameters in regression analysis resulted in sensory crispness predictions with $r = .99$.

The primary importance of material structure to the dynamics of food breakdown in the mouth, the sound emitted upon mastication, and the consumers response to these events makes rheological considerations critical to a more thorough understanding of the crispness sensation.

The Present Investigation

The current study will be a continuation of previously mentioned studies. To that end, it will be an attempt to outline relationships between sensory, acoustic, and mechanical parameters of foods differing in crispness levels (defined by water activity level) and consumers' appreciation of the ingested food. Two snack foods, each having distinct structural composition, will be used to assess the effects of mechanical parameters on the various sensory and acoustic parameters.

The sensory portion of the study will consist of consumers judging samples of two dry-crisp snack foods with distinct structural composition: Old London Melba Toast, having low density, large air content, and fairly uniform molecular composition; and Hostess/Frito-Lay Tostitos Tortilla Chips, with a dense, irregular composition, a very little air content. Whereas much of the previous research tested participants' ability to detect obvious product differences (e.g., Bisschop, 1995; Boehnke, 1996), the range of crispness for each product series will be restricted to smaller differences between adjacent a_w levels to observe whether participants can discriminate such differences. During this portion of the study, participant bite sounds will be digitally recorded and stored for acoustic analysis.

Previous research has not successfully related acoustic parameters to consumer hedonic judgments (i.e., different levels of crispness that result in different levels of appreciation). Thus, emphasis will be placed on the investigation of changes in the acoustic parameters of amplitude (root mean square, in volts) and frequency (in Hz) over various levels of crispness and how each of these parameters relates to their sensory correlate (i.e., loudness and pitch, respectively) and participants' pleasantness judgments.

Mechanical force-deformation properties of samples from each snack food and a_w

level will then be investigated with an Instron Universal Testing Machine, and compared to the sensory and acoustic data. Force-deformation curves will yield the mechanical parameters of apparent stiffness (N/mm)(i.e., slope of the curve) and peak force to fracture (Newtons).

Consequently, the objectives of the present study are: (1) To study consumer ratings of sensory crispness, loudness, and pitch, and an overall textural hedonic rating for two snack foods as function of water activity, a_w; (2) To study the acoustic measurements of amplitude and peak frequency of bite sounds emitted from each snack as a function of a_w, and to relate any changes in these measures to changes in sensory and/or hedonic ratings; (3) To study the mechanical properties of stiffness and peak force, derived from force-deformation curves, for the snacks as a function of a_w, and to relate any possible changes to the sensory, hedonic, and acoustic attributes of the snack foods. To this end, the research is an attempt to provide more information on the crispness sensation and its affinity to consumer appreciation of each of the specific snack food's under investigation.

METHOD

Participants

Seven female and five male students from the University of Guelph, ranging in age from 19-31 years, served as participants. By self report participants had natural dentition, no hearing problems, and no medical or hedonic aversion to the products being tested. Six participants were paid for their participation.

Materials

Two commercially available snack foods were purchased from a local grocery store: Old London Melba Toast and Tostitos Tortilla Chips (Hostess/Frito-Lay).

Sample Preparation

Before treatment, excessively browned slices of Melba toast were discarded as were overly curved and/or air-filled tortilla chips. Initial water activities, a_w, of the Melba toast and tortilla chips were analysed by a Thermoconstanter TH/RTD (Novasina, Switzerland) water activity meter at 25°C and found to be 0.20 and 0.06 respectively. Melba toast slices were then cut into approximately 2 cm x 2 cm squares and the tortilla chips were broken into rectangular shaped samples no larger than 5 cm x 5 cm. For each product, a subset of samples was stored in a dessicator over CaCl ($a_w = 0.0$) to prevent changes in each product's natural a_w level. A second set of samples of each product was dehydrated in an oven at 90 degrees Celsius for 72 hours to achieve an effective $a_w = 0.0$, and stored in a desiccator over CaCl ($a_w = 0.0$). The remaining samples of were divided into four groups and stored in evacuated desiccators over the following saturated salt solutions to achieve the desired water activity levels (in brackets): LiCl ($a_w = 0.11$),

$KC_2H_3O_2$ ($a_w = 0.23$), $MgCl_2$ ($a_w = 0.33$), and K_2CO_3 ($a_w = 0.43$). Samples were allowed to equilibrate for twenty-one days and remained in the desiccators until used.

Sensory Analysis

The method of paired comparison, as previously used by Bisschop (1995) and Boehnke (1996) in this type of study, was used to study participants' abilities in scaling sensory crispness, loudness, pitch, and overall textural acceptability (hereafter termed pleasantness). For each product, ratings were done after biting the comparison sample in each sample pair. Using the rating sheet provided, judges marked the level of the various sensory and hedonic attributes for that particular paired sample trial. Each line scale ranged from, for instance, "less crisp" (0) to "more crisp" (10), where judges were asked to consider the midpoint, "X" (5), of each scale as the standard's value for the particular attribute. A comparison perceived as less crisp than the standard in the trial pair was to be rated proportionally with a mark to the left of the "X" and a comparison perceived as more crisp was to be rated with a mark to the right of the "X".

Acoustical Analysis Apparatus

The acoustic signal emitted from each sample when bitten was received by a Sony Electret low impedance condenser microphone (model ECM-150T) mounted on a pair of tweezers that was used to grasp the sample to be bitten. From there the signal was passed through a DC voltage preamplifier (gain = 50X), and into a SoundBlaster 16 bit sound card in a 386-enhanced PC with a sampling rate of 8 bits per second at 44.1 kHz. The sampling methods ensured accurate, highly detailed, tape quality, mono sound recordings capturing frequencies between 0-20.0 kHz, and thus allowed observation of any frequencies above 10.0 kHz; frequencies previously considered irrelevant (Lee et al., 1988). The digitized sound obtained was cropped to a 400 ms segment and saved as a sound file for subsequent analysis.

Amplitude and frequency analyses were performed using Signal Analyser software (Dr. J. Vanderkooy, University of Waterloo). The amplitude value obtained for the 17640 bytes per 400 ms bite sound was the root mean square (in volts). Frequency analysis of each 400 ms bite sound involved having a computer do a 2048 point Hanning window Fast Fourier Transform (FFT) which was graphically represented as the accumulated power spectrum. This allowed the determination of the peak frequency: the frequency of the highest amplitude peak present in the power spectrum.

Mechanical Force-Deformation Analysis

Samples of each product were allowed to equilibrate to the five a_w levels used for the sensory and hedonic testing for twenty-one days. Five samples from each a_w level of each snack were subjected to compression analyses on an Instron Universal Testing Machine Model 1122 (Instron Corporation, Canton, MA) with a crosshead speed of 20 mm/min. Data were acquired by an interfaced computer using Merlin Series IX software. Apparent stiffness (N/mm) and peak force (N) were determined from the resulting force-deformation curves.

Whole Melba toast slices were subjected to a three-point snap test by a cylindrical blade (radius = 3 mm). Slices were placed on two similar blades separated by a 5 cm gap and each sample was fractured with the longitudinal axis perpendicular to the blade. The tortilla chip samples were broken into approximately 5 cm x 5 cm flat rectangular pieces without air bubbles and subjected to a punch test with a 3/16 inch diameter flat head cylindrical probe.

Procedure

Each participant was tested individually within a single session of approximately forty minutes. Before testing, the researcher provided an instruction sheet, demonstrated the desired orientation of Melba toast samples and biting method, asked the participant to practice biting chip samples with the appropriate method, and answered procedural questions. Pitch awareness was tested by having the participant discriminate different frequency pure tones emitted from a signal generator and presented through a speaker located on top of the table, in front of the participant. The particpant then confirmed his/her understanding of the remaining sensory and hedonic attributes to be judged. Participants were seated in front of a table containing the following items: one pair of tweezers with a mounted microphone, one pitcher of water, one drinking glass, two data sheets containing rating scales, a wooden block with mounted speaker, and two product series, each aligned in two rows of eighteen labelled cups, where, for each series, the row closest to the participant contained the standard samples.

Six participants judged the tortilla chips followed by the Melba toast, and the remaining six judged the Melba toast followed by the tortilla chip. Participants judged each product series using the paired-comparison method with standard, in which each test sample was compared with a standard sample and the standard was compared to itself. Each product series was divided into three blocks of six randomized samples, each sample corresponding to one of the six a_w levels. Therefore, each participant judged each of six

a_w levels three times for each product, making a total of 18 judgments per product.

The participant used the tweezers to remove the standard from the first row and held it above the wooden block in front of the speaker. After hearing a tone cue from the speaker, the participant placed the sample between the incisors, keeping lips clear of the sample, and bit down evenly until the sample fractured, listening for the sensory attributes to be judged. The participant then spat out the remnants of the standard and removed the first comparison sample from the cup labelled "1" in the second row. Again, after hearing the tone, the comparison was bitten as before and judged, in comparison to the standard, for its crispness, loudness, pitch, and pleasantness on the rating scales provided. This procedure was repeated for the eighteen samples of each product, with the participant free to rinse his/her mouth anytime during the session.

After the test session each participant was asked which attribute he/she found most easy to judge, and on what basis his/her crispness judgments were made, if they were not based on the other attributes rated.

RESULTS

Analyses were done in the following four ways: (1) Each sensory and hedonic rating was subjected to a 2 x 5 (Product x Water Activity Level) repeated measures ANOVA (analysis of variance) and subsequent pair wise t-tests; (2) Instrumental acoustic data was collected from the analysis of each 400 ms bite sound. Amplitude values were obtained as the root mean square (in volts) of each bite sound. Fast Fourier Transformations (FFTs) were done for each bite sound and resulted in graphically represented power spectra from which peak frequency values, representing the highest amplitude peak per power spectrum, were determined. A 2 x 5 (Product x Water Activity Level) repeated measures ANOVA and subsequent pair wise t-tests were performed on the data; (3) Pearson correlations were then computed for all sensory, hedonic, and acoustic values; (4) Finally, the instrumental mechanical parameters of apparent stiffness (N/mm) and peak force to fracture (N) were derived from the force-deformation curves and informally compared with sensory and hedonic ratings along with the acoustic parameters.

Sensory Analysis

Since decreased product crispness often results in decreased consumer appreciation of the product, sensory ratings for products of altered a_w levels were investigated to observe which attributes covary, and if such changes coincide with consumer overall textural hedonic ratings. For each treatment level of both snacks, participants' three ratings of each sensory and hedonic attribute were separately combined to yield a single mean for each of the four attributes. The means were collapsed across judges to yield overall mean sensory and hedonic scores for each a_w level of each product. Unaltered (i.e., standard) samples of each product (Melba toast $a_w = 0.20$ and tortilla chip $a_w = 0.06$) were excluded from the analysis.

Insert Figures 1-4 and Table 1 about here

Figures 1-4 and Table 1 show the general decrease of sensory crispness, loudness, pitch, and pleasantness with increased a_w for both products. Excluding $a_w = 0$ for both products, both Crisp and Loud ratings followed a trend of decreasing means with increasing a_w level (the higher the number the higher the moisture content). While a similar trend is observed for Pitch judgments of tortilla chips beyond the lowest a_w level, Pitch ratings for the Melba toast are stable until $a_w = 0.23$, then begin to drop. Pleasantness ratings of Melba toast appear unchanged across a_w levels, but those of the tortilla chips show decreases across a_w levels, with $a_w = 0.43$ eliciting a mean nearly half that of $a_w = 0.11$, the a_w level with the highest Pleasantness rating. As can be seen in Table 1, the total number of pair-wise differences for the tortilla chips is larger (18) than that for the Melba toast (13). Whereas no pleasantness differences were found between Melba toast water activity levels, ranking it last in total number of differences, tortilla chip pleasantness ratings tied with Melba toast pitch ratings in the production of the most differences (6). When the sensory and hedonic means for each water activity level are averaged for each product, as seen in Appendix A, the mean rating is larger for the Melba toast than the tortilla chip for each sensory rating and the hedonic rating.

A 2 X 5 (Product x Water Activity Level) repeated measures ANOVA (see Appendix B) and subsequent pair wise t-tests were done on participants mean sensory and

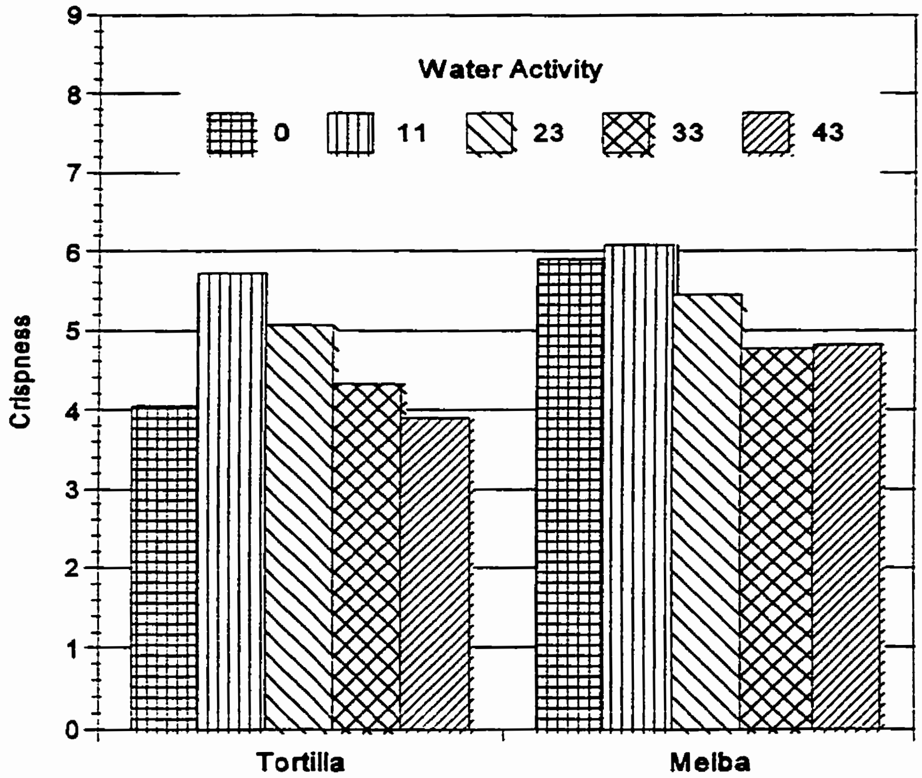

Figure 1. Mean crispness ratings as a function of water activity for two snack foods.

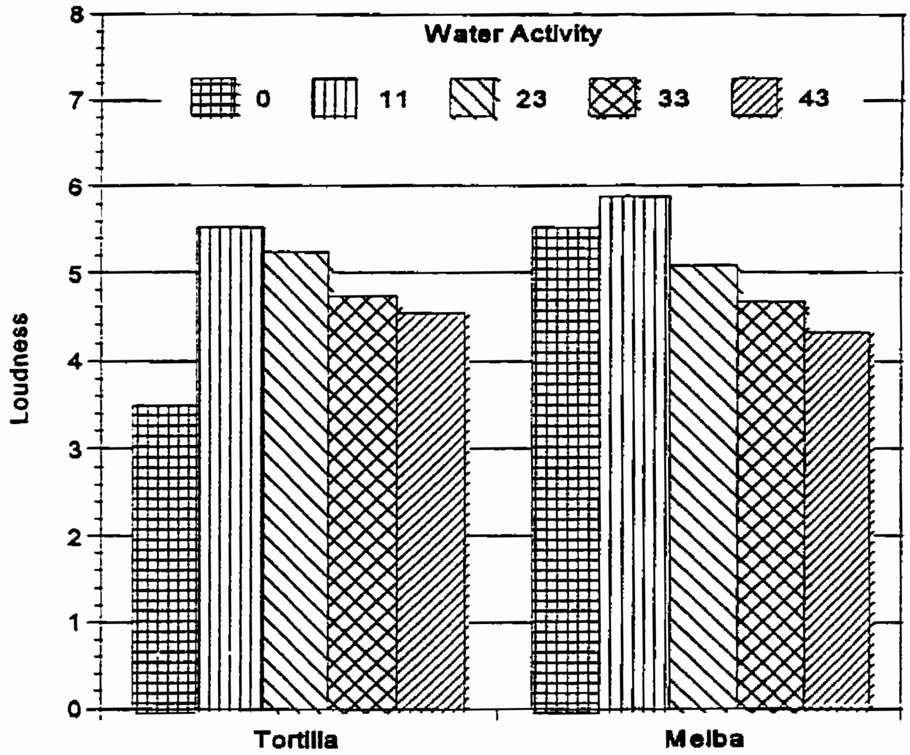

Figure 2. Mean loudness ratings as a function of water activity for two snack foods.

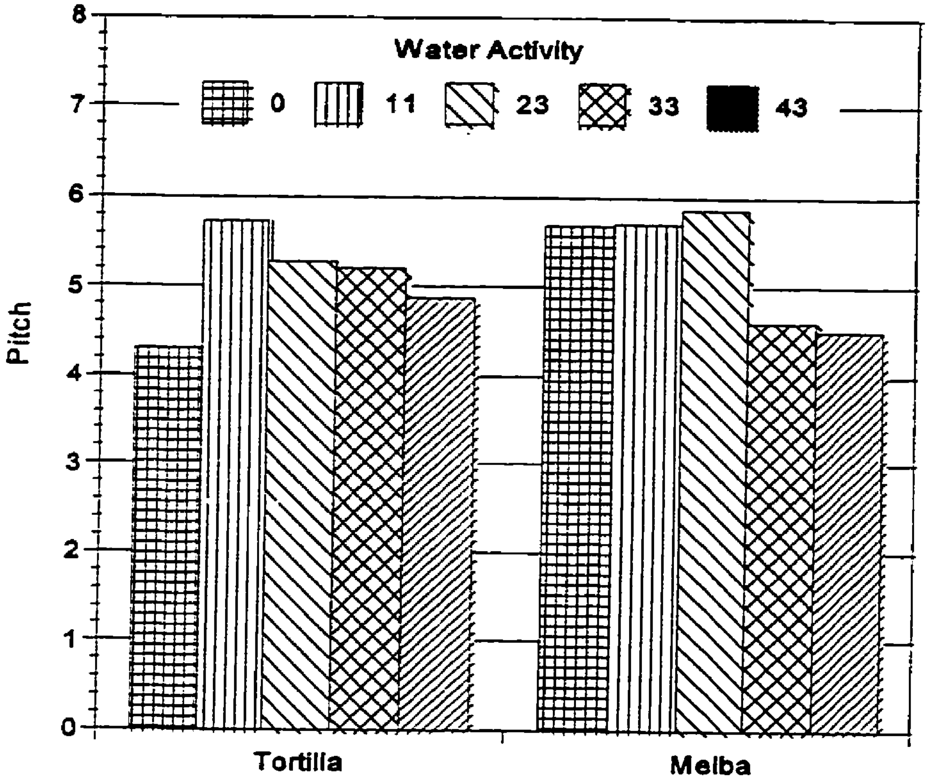

Figure 3. Mean pitch ratings as a function of water activity for two snack foods.

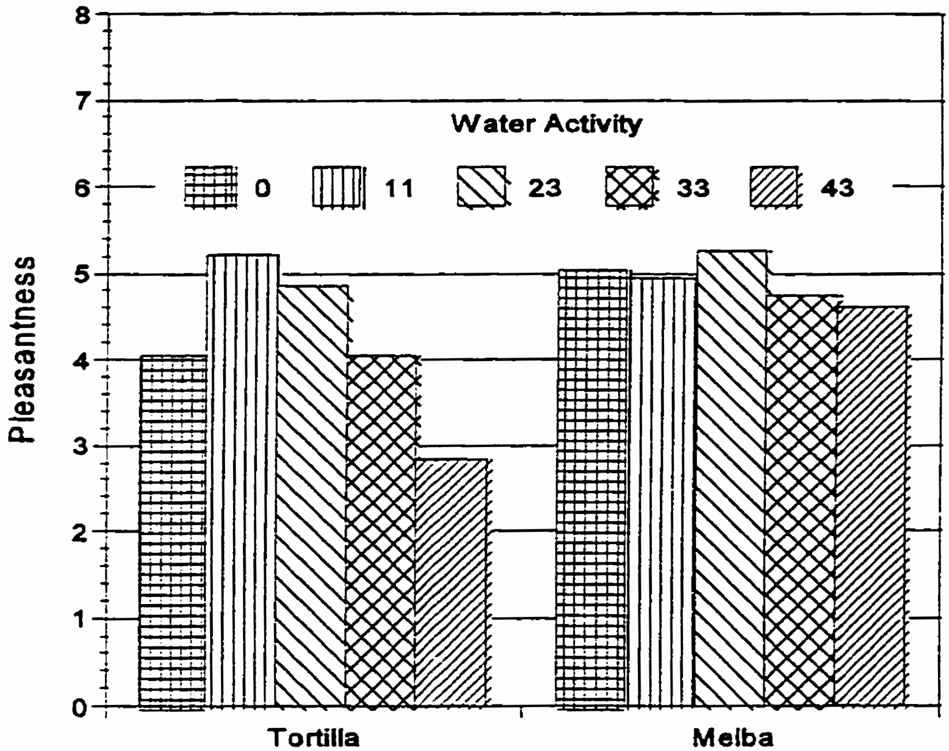

Figure 4. Mean pleasantness ratings as a function of water activity for two snack foods.

Table 1.
Mean Crispness Intensity Ratings For Two Snack Foods As A Function of Water Activity (N=12).

	Product			
	Melba Toast		Tortilla Chip	
a_w	Mean	SD	Mean	SD
		Crisp		
0	$5.903_{a,b}$	1.182	4.049_{a}	1.387
0.11	$6.090_{c,d}$	1.214	$5.722_{a,b,c}$	0.759
0.23	5.451	0.993	5.069_{d}	0.922
0.33	$4.764_{a,c}$	1.175	4.340_{b}	1.353
0.43	$4.806_{b,d}$	1.208	$3.910_{c,d}$	1.346
		Loud		
0	5.533_{a}	1.074	$3.493_{a,b}$	0.793
0.11	$5.882_{b,c}$	1.080	$5.521_{c,d}$	1.083
0.23	5.090	0.947	5.250_{e}	0.728
0.33	4.681_{b}	1.184	$4.743_{a,c}$	1.218
0.43	$4.327_{a,c}$	1.145	$4.535_{b,d,e}$	1.391
		Pitch		
0	$5.679_{a,b}$	1.163	$4.306_{a,b}$	1.459
0.11	$5.701_{c,d}$	1.118	$5.715_{a,c}$	0.634
0.23	$5.868_{e,f}$	1.130	5.285	1.234
0.33	$4.604_{a,c,e}$	1.261	5.208_{b}	1.621
0.43	$4.521_{b,d,f}$	0.923	4.875_{c}	1.565
		Pleasant		
0	5.026	0.860	$4.056_{a,b}$	1.373
0.11	4.938	1.039	$5.222_{a,c,d}$	0.877
0.23	5.263	0.892	4.847_{e}	1.004
0.33	4.743	1.199	$4.048_{c,f}$	1.447
0.43	4.618	1.283	$2.826_{b,d,e,f}$	1.293

Note. Means sharing the same subscript are significantly different from each other (p=.05).

pleasantness judgments using SYSTAT statistical software. The alpha level was equal to .05 for all tests. With the exception of mean Pleasantness ratings for the Melba toast ($F_{4,44}$ = 0.658, p=.625, MS_{error} = 1.621) mean judgments of the remaining sensory attributes were significantly different across a_w levels of both products. Summaries of the ANOVA components and the corresponding effect sizes can be seen in Appendix C. A series of t-tests was done to find the a_w levels contributing to the significant F-values and the results are presented in Table 1. Interestingly, tortilla chip pleasantness and loudness ratings yielded more significant differences among a_w levels than did crispness ratings, and pitch had the least differences. The opposite pattern is observed for the Melba toast, where no pleasantness differences were reported and Pitch elicited more differences than either of Loud or Crisp.

Acoustic Analysis

It was suggested that food products of altered moisture contents differ in crispness based on variations in loudness (e.g., Drake, 1963) and/or pitch (e.g., Vickers, 1987, 1988; Boehnke, 1996). To investigate this hypothesis, the acoustic parameters of amplitude and frequency were analyzed for each bite sound using a 2 x 5 (Product x Water Activity Level) ANOVA for each parameter (see Appendix B). Amplitude was measured as a root mean square (rms, in volts) and frequency was measured as the peak frequency obtained from the recorded power spectra.

Insert Figure 5 and Table 2 about here

Table 2 shows mean amplitude (volts) and mean peak frequency (largest amplitude peak) of the three bite sounds from each product at all a_w levels. As can be seen in Figure 5,

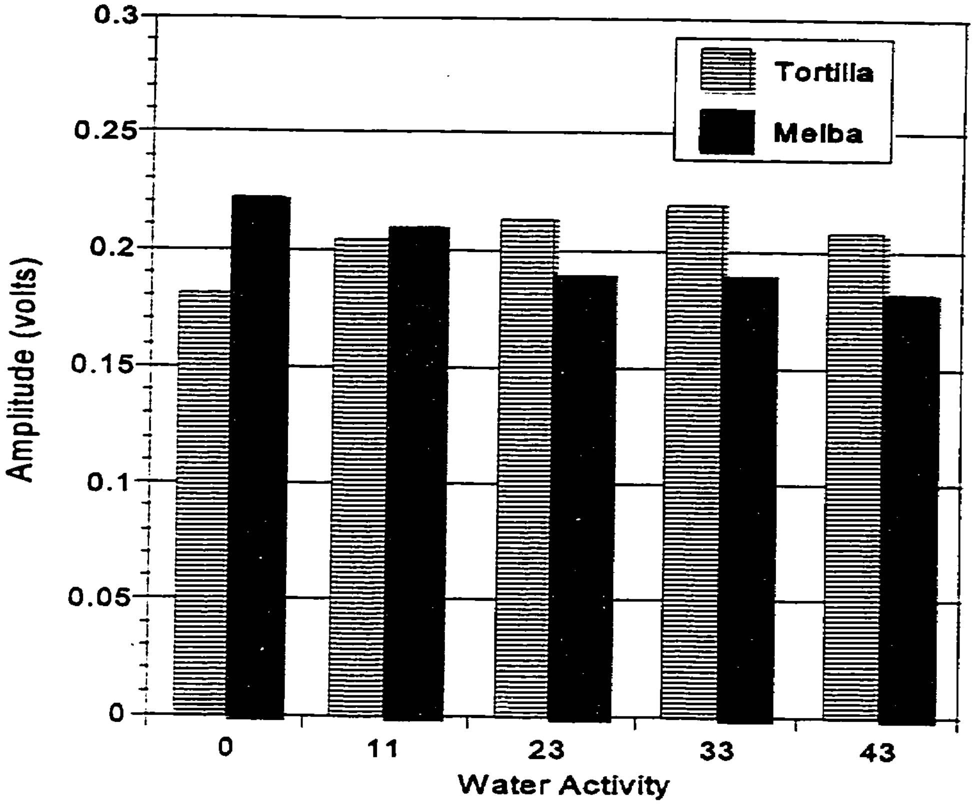

Figure 5. Mean amplitude (volts) as a function of water activity for two snack foods.

Table 2.
Mean Acoustic Measures of Snack Foods At Each a_w Level (N=12)

	Product			
	Melba Toast		Tortilla Chip	
a_w	Mean	SD	Mean	SD
		Amplitude (rms volts).		
0	0.222	0.025	0.181	0.020
0.11	0.209	0.019	$0.204_{a,b}$	0.021
0.23	$0.189_{a,b}$	0.015	$0.213_{a,c,d}$	0.027
0.33	0.189_{a}	0.019	$0.219_{c,e}$	0.023
0.43	0.182_{b}	0.021	$0.208_{b,d,e}$	0.026
		Frequency (Hz)..		
0	2120	1387	5699	2318
0.11	1661	1000	4222	2624
0.23	1964	911	4324	1633
0.33	2728	1340	3932	2832
0.43	2221	1080	6074	3928

Note. . Means sharing the same subscripts are not significantly different from each another (p >.05).
.. No significant differences were found.

mean amplitude values decrease with increasing a_w levels for the Melba toast bite sounds, while the tortilla chip bite sounds show a tendency toward greater amplitudes with increasing a_w levels. Furthermore, Table 2 shows the small standard deviations associated with each treatment level for both products. While no between products differences were found, a_w level affected bite sound amplitude for the Melba toast ($F_{4,40}$ = 18.613, p <.0001, $MS_{error} = 1.5 \times 10^{-4}$) and the tortilla chip ($F_{4,40}$ = 5.139, p =.002, $MS_{error} = 4.5 \times 10^{-4}$). The subsequent pair wise comparisons revealed that comparisons of Melba toast amplitudes were significant (p <.05) with two exceptions: the mean amplitude of a_w= 0.23 was not different from that of either a_w= 0.33 or a_w= 0.43. Fewer pair wise differences were noted for the tortilla chip bite sounds where the mean amplitude of a_w = 0 differed from that of all other a_w levels (p <.05), yet no other differences were observed.

Insert Figures 6 and 7 about here

Power spectra peak frequencies below 750 Hz were omitted from statistical analysis since peaks in this range failed to discriminate between products. Figures 6 and 7 show typical power spectra for a Melba toast and a tortilla chip bite sound, respectively. The mean peak frequencies seen in Table 2 reflect the diversity of frequencies seen between products, with tortilla chip bite sounds producing higher peak frequencies than the Melba toast bite sounds. As well, the standard deviations of the tortilla chip bite sounds are almost twice those reported for the Melba toast, indicating the large range of high amplitude peak frequencies present. The large standard deviations likely resulted in the lack of peak frequency differences within each product across a_w levels (p =.05).

Insert Tables 3-5 about here

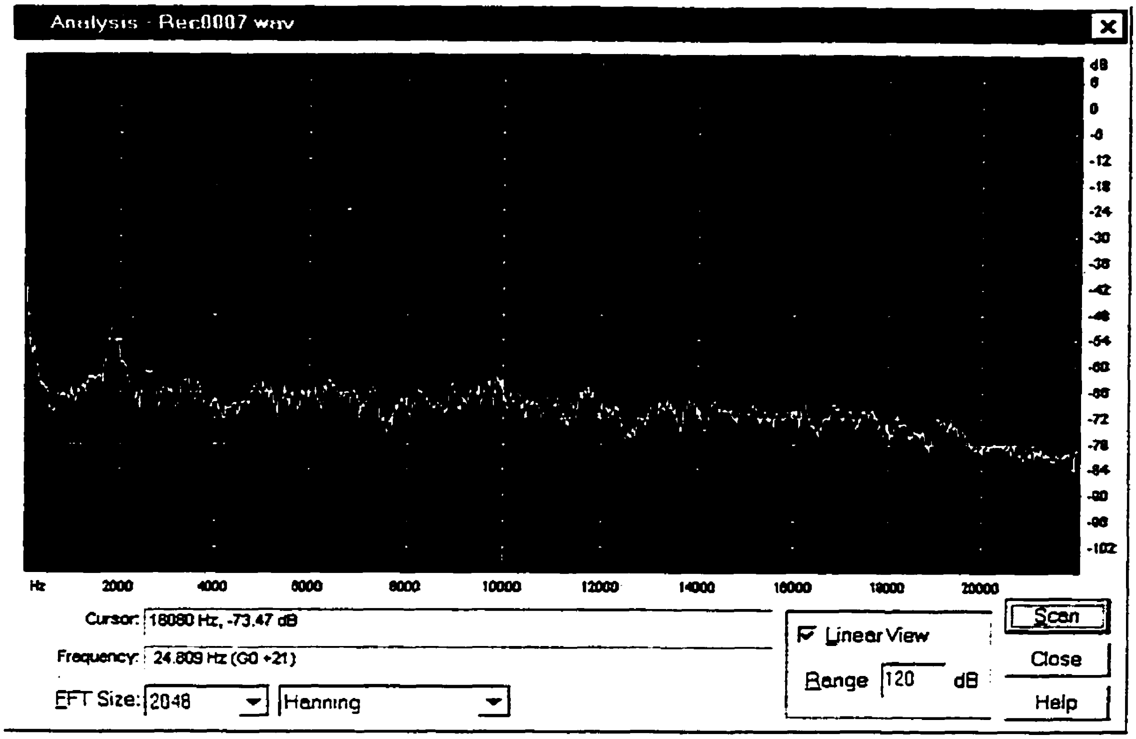

Figure 6. Power spectrum of a Melba toast bite sound.

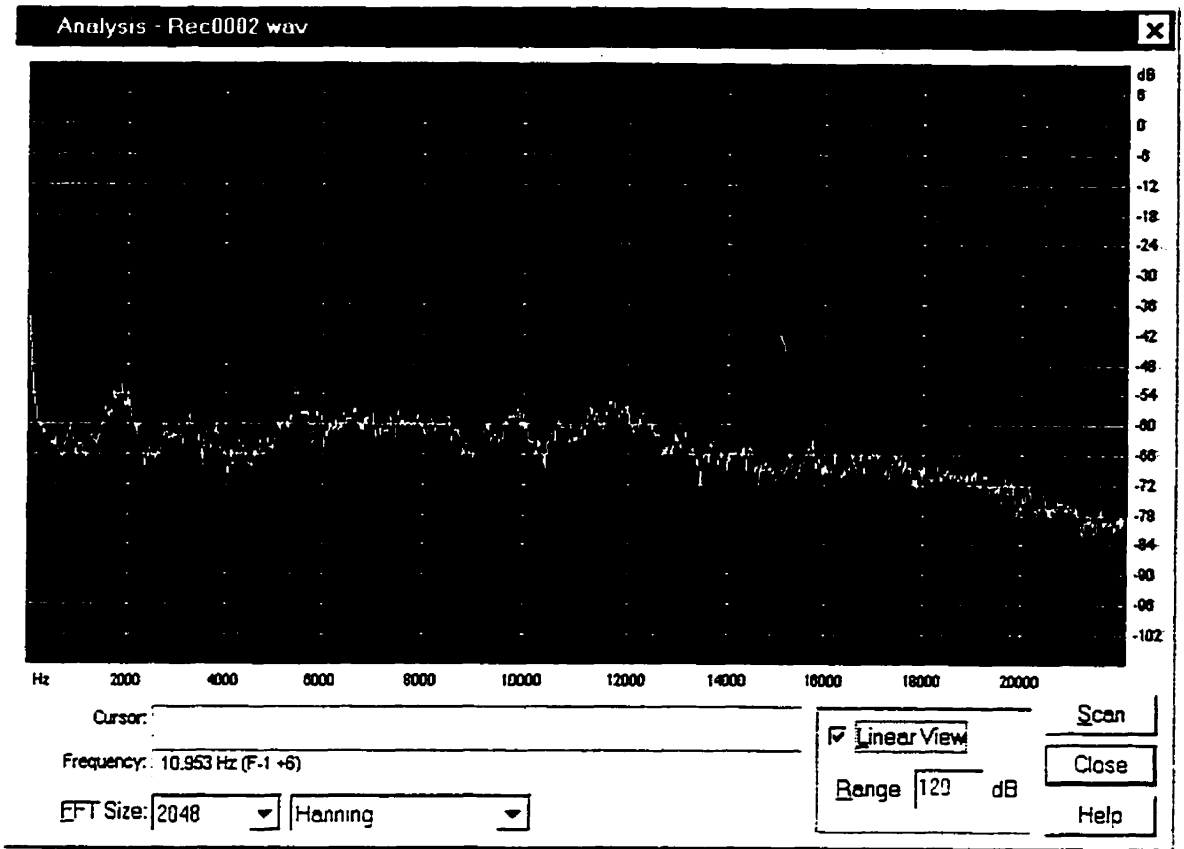

Figure 7. Power spectrum of a tortilla chip bite sound.

Table 3.
Overall Pearson Correlation Matrix of Sensory and Hedonic RatingsFor Two Snack Foods (N=110).

Attribute	1	2	3	4
1. Crisp	--	0.784	0.438	0.478
2. Loud		--	0.555	0.331
3. Pitch			--	0.194.
4. Pleasant				--

Note. . $p > .10$. Remaining correlations are significant with $p < .007$.

Table 4
Pearson Correlation Matrix of Sensory and Hedonic Ratings With Acoustic Measures For Melba Toast (N = 55).

Attribute	1	2	3	4
1. Crisp	--	0.868	0.724	0.251
2. Loud		--	0.699	0.124
3. Pitch			--	0.180.
4. Pleasant				--

Note. . $p > .10$. Remaining correlations are significant with $p < .01$.

Table 5
Pearson Correlation Matrix of Sensory and Hedonic Ratings ForTortilla Chip (N = 55).

Attribute	1	2	3	4
1. Crisp	--	0.696	0.196 .	0.562
2. Loud		--	0.425	0.429
3. Pitch			--	0.184
4. Pleasant				--

Note. . $p > .10$. Remaining correlations are significant with $p < .017$.

To observe possible interrelations between the sensory, hedonic, and acoustic attributes, Pearson correlation matrices with Bonferroni adjusted probabilities were constructed and are presented in Tables 3-5. As can be seen in Table 3, the highest correlation across mean product ratings collapsed across the two snacks was between Crisp and Loud ($r = .784$), followed by Pitch and Loud ($r = .555$) and Pleasant and Crisp ($r = .478$). Table 4 and 5 respectively show the correlations for Melba toast and tortilla chip. Again, Crisp and Loud display the highest correlation for the Melba toast ($r = .868$) and the tortilla chip ($r = .696$). Interestingly, ratings of Crisp and Pitch were highly correlated in Melba toast ($r = .724$) but were not significantly correlated for the tortilla chip ($r = .196$, $p > .10$). Also notable is the lack of a significant correlation between Crisp and Pleasant ratings for the Melba toast ($r = .251$, $p > .10$) while it was the second highest correlation for tortilla chip ratings ($r = .562$). While the correlation between Amplitude and Loud was significant across both products ($r = .332$) combined and for Melba toast ($r = .448$), it was not significant for tortilla chips ($r = .293$, $p > .10$). Other than the two exceptions mentioned, amplitude and peak frequency measurements showed no significant correlations with any of the sensory ratings, the hedonic rating, or with one another.

Mechanical Force-Deformation Analysis

Data gathered for the Melba toast (three point snap test) and tortilla chip (puncture probe test) were analysed, first strictly as mechanical parameters, and then were informally analysed through plots with the sensory and acoustic parameters. For the Melba toast, all raw Instron curves were inspected for reproducibility prior to averaging. Any curve that seemed inconsistent, due to multiple fractures of a sample, was not included in the average; a minimum of three curves were used in each analysis. Due to the irregular and convex shape of the tortilla chips, the fracture patterns of the samples were highly variable. Consequently, data collected from the puncture probe test included samples that demonstrated multiple fractures. Multiple fracturing resulted in bimodal force-deformation curves dissimilar to the single peak curves obtained for single fracture tortilla chip samples and all Melba toast samples. Consequently, individual curves were not averaged together, rather the apparent stiffness and peak force were calculated separately for each. Peak force measurements were robust against multiple fractures and displayed normal variability, so each average includes each of the five samples per a_w level. However, the apparent stiffness values were more sensitive to multiple peaks and such inconsistent values were discarded and an average was calculated for the remaining values. Again, a minimum of three values was used in each analysis. Peak force (N) represents the highest force reached in the particular test. Apparent stiffness (N/mm) is derived from the slope of the initial part of the force-deformation curve and is calculated by linear regression of the linear region of the peak. Higher stiffness values result from a greater force necessary to deform a sample prior to fracture.

Insert Figures 8 and 9 and Table 6 about here

As seen in Figure 8 and Table 9, peak force measurements of the tortilla chips seem to steadily increase as a_w level increases, while those for Melba toast apparently increase until $a_w = 0.23$, after which they tend to decrease. The trend of increasing peak force with higher a_w levels indicates that more force becomes necessary to bring the sample to fracture. The apparent stiffness values of the tortilla chips, also seen in Table 6

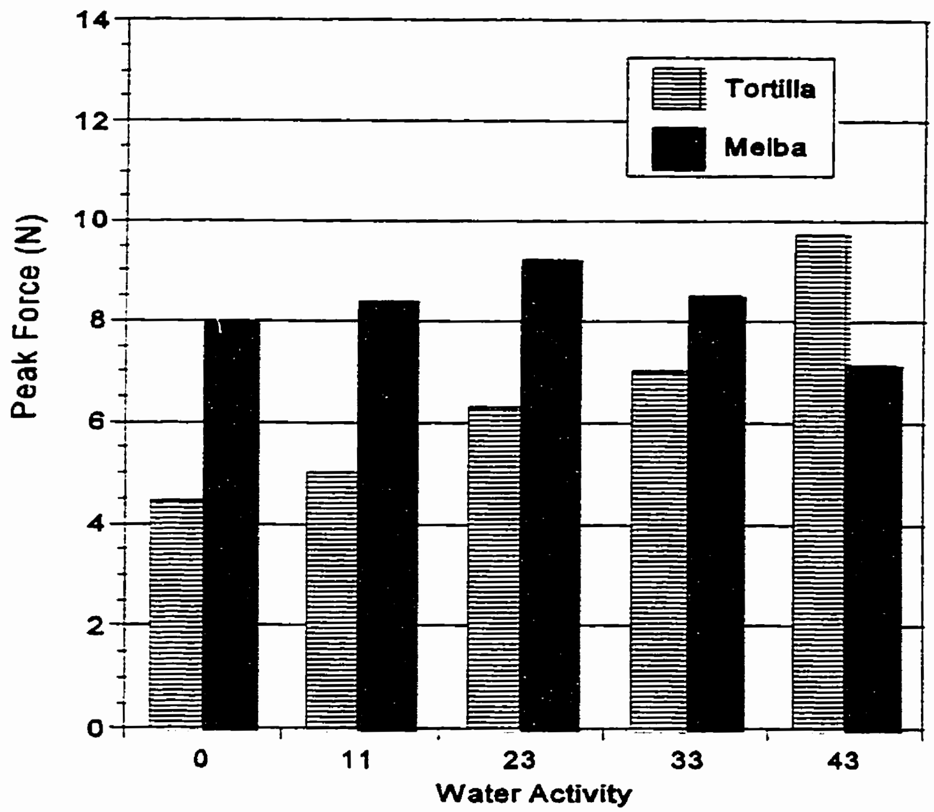

Figure 8. Mean peak force (N) as a function of water activity of two snack foods.

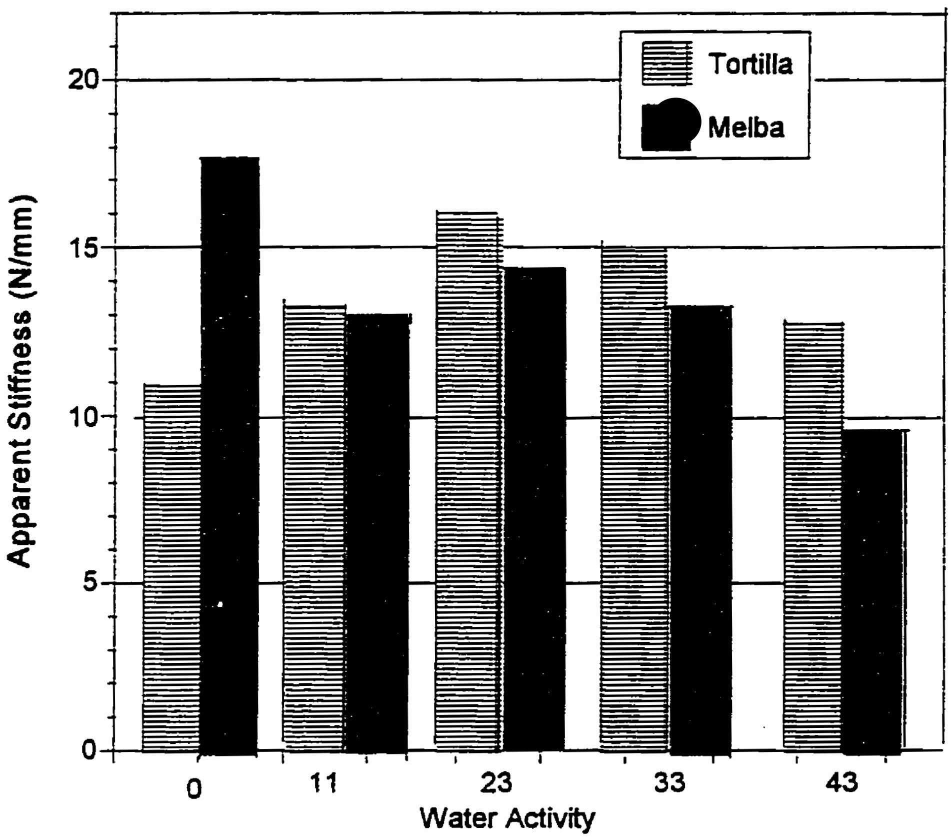

Figure 9. Mean apparent stiffness values (N/mm) as a function of water activty for two snack foods.

Table 6.
Influence of Water Activity on Peak Force and Apparent Stiffness of Two Snack Foods.

	Product			
	Melba Toast		Tortilla Chip	
a_w	Peak Force (N)	Apparent Stiffness (N/mm)	Peak Force (N)	Apparent Stiffness (N/mm)
0	7.95	17.63	4.47	10.92
11	8.37	12.90	5.01	10.54
23	9.22	14.27	6.30	12.74
33	8.50	13.25	7.03	13.94
43	7.12	9.59	9.72	11.85

and plotted in Figure 9, increase until $a_w = 0.23$ after which they begin to decline, similar to that observed for the Melba toast, excepting the lowest water activity level that had the highest apparent stiffness value. The decrease in apparent stiffness with increasing a_w level indicates that the higher a_w samples deform more than do lower a_w samples when under an identical force. Thus, the higher a_w samples are more pliable, capable of a greater deformation prior to fracture than that for low a_w samples.

Insert Figures 10-12 about here

When peak force means are plotted against sensory and acoustic means a few interesting relationships emerge. First, Figure 10 illustrates for the tortilla chip, with one exception, a trend of increasing amplitude and peak force measurements; a trend not shared by the Melba toast. Figures 11 and 12 respectively show the relationships for each product between peak force and sensory crispness and peak force and pleasantness. Both relationships for the tortilla chip show, excluding one instance in each figure, the sensory rating decreases with concurrent peak force increase. Similar trends are not seen for the Melba toast.

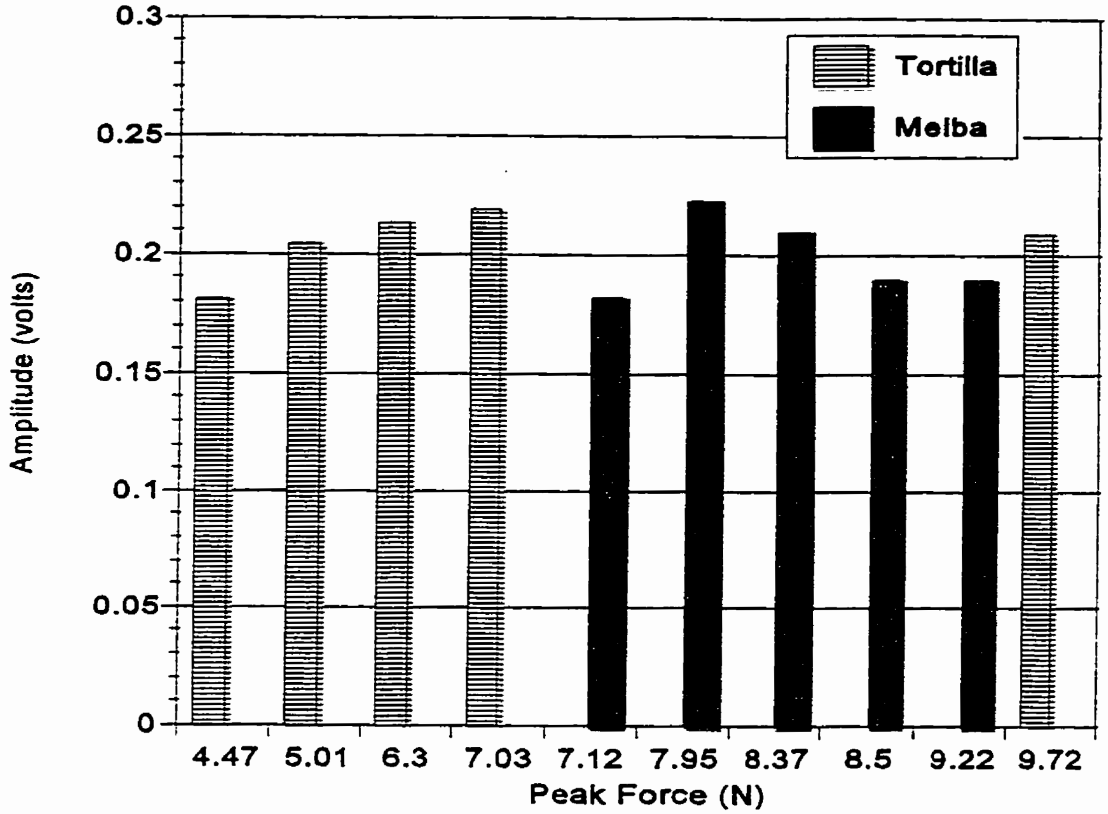

Figure 10. Mean amplitude values (volts) versus mean peak force values (N) for two snack foods

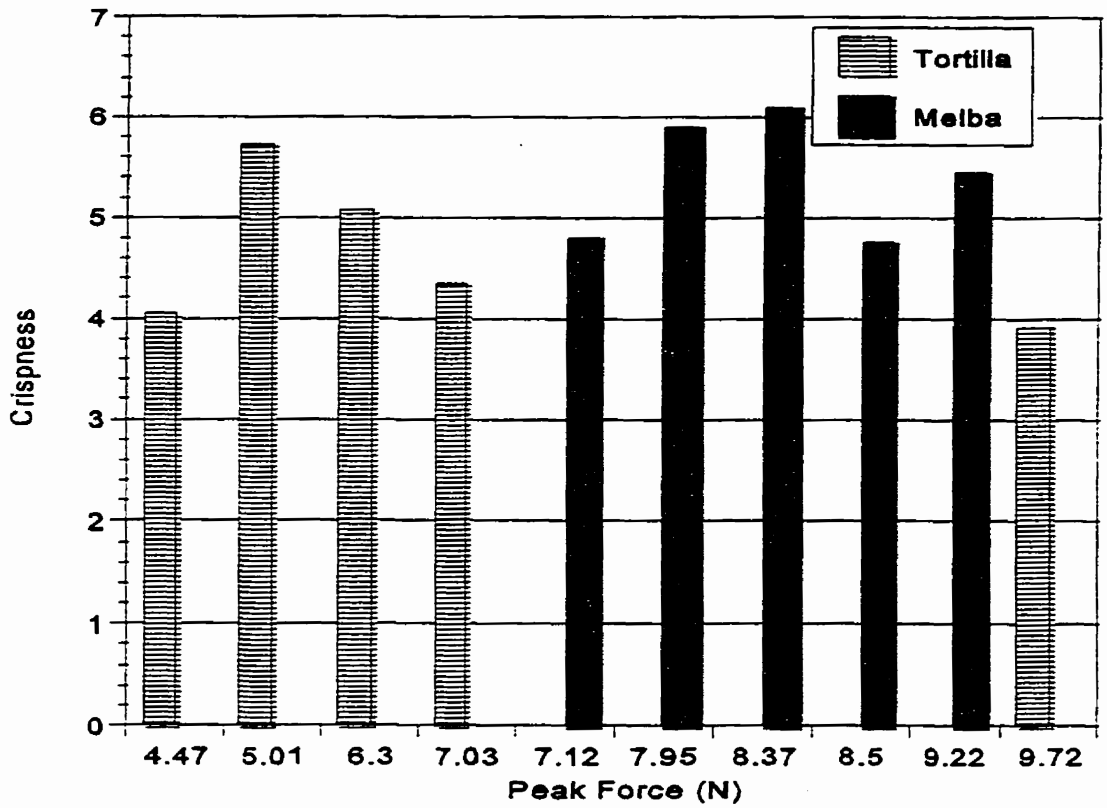

Figure 11. Mean crispness ratings versus mean peak force values (N) for two snack foods.

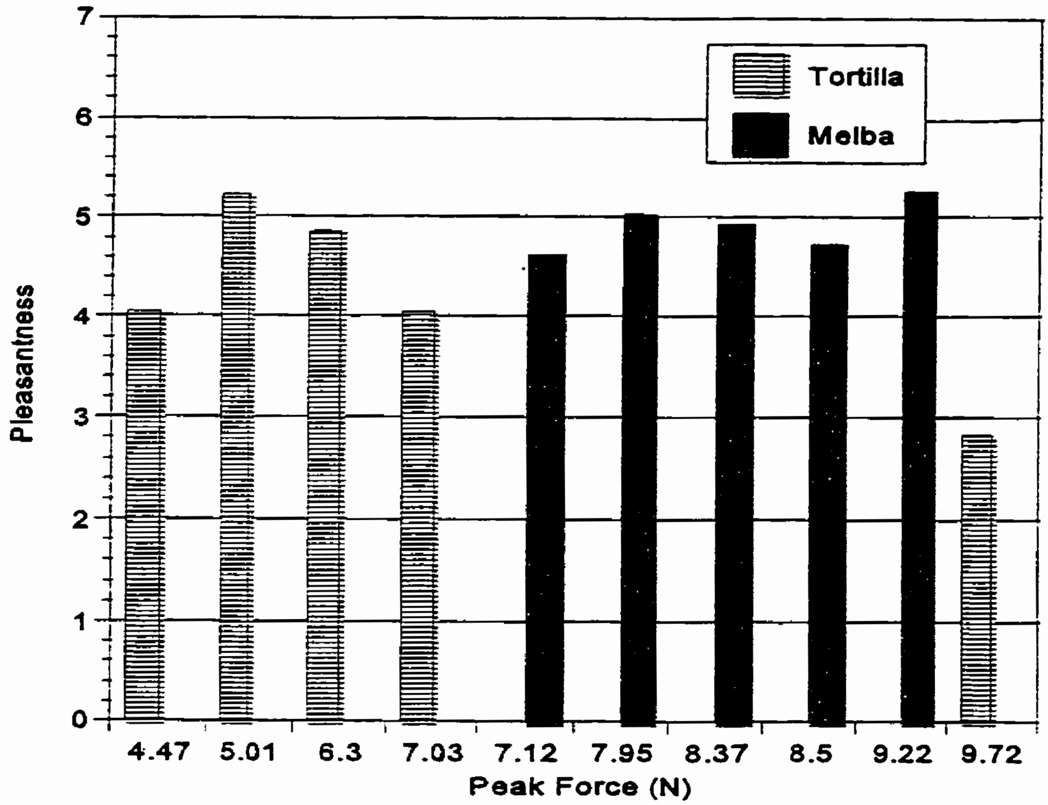

Figure 12. Mean pleasantness ratings versus mean peak force values (N) for two snack foods.

DISCUSSION

The present results represent both a methodological refinement upon and advancement of similar research conducted by Bisschop (1995) and Boehnke (1996) while offering additional evidence for the Psychoacoustical Theory of Crispness (Vickers & Bourne, 1976b). Specifically, the methodological advancements were: the exertion of more control over product moisture content, defined here by water activity level; including moisture differences smaller than had previously been tested; and power spectra frequency analysis of the recorded bite sounds which permitted a clear and effective method for determining the relevant frequency components in food bite sounds.

Sensory Analysis

The first objective of the study was to determine whether untrained consumers could use the paired-comparison method successfully to scale their perceptions of crispness, loudness, pitch, and pleasantness of two products as a function of water activity level. With few exceptions, the data show that sensory and hedonic ratings of the two snacks decreased as a_w increased, confirming studies of other dry-crisp products (e.g., Bisschop, 1995; Boehnke, 1996; Katz & Labuza, 1981; Sauvageot & Blond, 1991). The differences between adjacent water activity levels used in this study were chosen to make discrimination difficult. Based on the small number of pair-wise differences observed, the results show that participants did find samples harder to discriminate than was previously observed by Bisschop (1995) and Boehnke (1996). In analyses of participants sensory and pleasantness judgments of tortilla chips, a greater number (6) of pair-wise differences were significant for pleasantness ratings than for loudness (5), crispness (4) and pitch (3) ratings. The Melba toast ratings showed an inverse pattern with more differences in pitch ratings (6) than those of crispness (4), loudness (3), or pleasantness (0). It could be that, since there were more differences in pleasantness ratings of tortilla chips than for any other tortilla chip rating scale, participants may have based their pleasantness judgments on some attribute(s) other than those rated. If, as suggested here, paticipants did encorporate into their ratings some attribute(s) other than those explicitly rated, such an observation might also explain why Melba toast sensory differences failed to manifest themselves hedonically; that is, participants may have implicitly based their judgments on similar untested attributes of the snack foods, but these untested attributes could have different importance depending on the specific snack food that is bitten.

The present study is the first study to unequivocally demonstrate participants' abilities to scale the pitch of snacks differing in water activity levels and offers support for Vickers' (1984, 1985) contention that food sounds may be discriminated by pitch. Using particular products designated as crisp or crunchy, Vickers reported that raters found bites of crispy foods were higher in pitch than bites of crunchy foods, and that bite sounds were generally of higher pitch than chew sounds. The present data show that judges can scale differences in pitch based on the water activity level of a particular product, not solely on the basis of eating method. Furthermore, judges discriminated the pitch of the Melba toast, which could be considered more crunchy than the tortilla chips, better than any other single attribute rated. So, while high pitch sounds seem to discriminate between crisp and crunchy foods, they are not necessary for discrimination between samples of different water activity. Assuming that all judges have previous experience with Melba toast and that the usual manner of eating Melba toast would be a molar chew rather than an incisor bite, it is possible that the novelty of the eating method permitted judges to attend more to the pitch of the Melba toast than to that of the tortilla chips. The tortilla chips would be eaten in a similar manner to that prescribed here, thus the situation may have afforded less novel stimuli and allowed a more balanced approach to the ratings.

Post-test interviews revealed that participants incorporated into their notion of crispness a subjective measure of how hard they had to bite down to break a sample, with increasing crispness related to increasing product hardness or force-to-fracture. Such self-reports contrast the present data that show decreased crispness ratings with increased peak force values. Seymour and Hamann (1988) also reported that sensory crispness was inversely correlated to sensory hardness ($r = -.87$), and Vickers (1987) report that oral and auditory crispness were inversely correlated with mechanical breaking force ($r = -.46$ and $r = -.01$, respectively).

In general, the present data show that consumers can rate crispness reliably as a function of water content. Furthermore, crispness seems to be related to a consumer's recognition of loudness and pitch, and it has been shown to contribute to a product's acceptance by the consumer: more crisp products are generally better appreciated by consumers. These findings point to a potential advantage to be gained by dry-crisp product manufacturers if they were to consider how crisp a product could be made. Structural and mechanical analyses will undoubtably support these observations, since the sound produced by a food is the result of the vibration characteristics of the product's composition.

Acoustic Analysis

The second objective of the study was to determine which, if any, acoustic measurements best characterize crispness. While previous research of food crispness often used inadequate or complicated analysis methods, the present study attempted to simplify the process of sound characterization. Edmister and Vickers (1985) successfully combined individual acoustic measurements into more complex parameters with the hope of characterizing crispness, reporting that sensory crispness of dry foods was correlated with the logarithm of the product of the number of sound peaks multiplied by the mean height of the peaks ($r = 0.66$). Seymour and Hamann (1988) analyzed the frequency components of crisp sounds, but only considered frequencies between 500 and 3500 Hz, whilst Lee et al. (1988) investigated only those frequencies below 8 kHz, although they noted that interpretive problems arise when sound intensities above 8 kHz are considered. That is, they noted that sounds above such frequencies are less appreciated due to the nonlinear intensity-frequency response characteristic of humans. The present study aimed to simplify the acoustic analysis. Bite sound amplitude was calculated as the root mean square (in volts) and frequency analysis considered all frequencies between 750 - 20 000 Hz, with the peak frequency (Hz) characterized as the single highest amplitude peak of the power spectrum.

Lee et al. (1988), in confirming previous work, showed that increased water activity resulted overall in significantly lower airborne sound amplitudes. Interestingly here, the amplitude of Melba toast bite sounds decreased as water activity increased, as reported by Boehnke (1996), but the corn-based tortilla chip sound amplitude increased with higher water activity values. Seymour and Hamann (1988) reported similar amplitude increases for another corn-based product, the Keebler Crunch Twist. Unlike the present tortilla chip data, Seymour and Hamann's participants' loudness ratings increased as measured sound amplitude increased. However, the authors used crushing sounds obtained from samples crushed with a shear/compression cell, and not the sounds emitted from the participants biting the samples. Perhaps increasing amplitude with increased water activity may be related somehow to the dense structure of the corn-based tortilla chip, possibly resulting in different mechanical behaviour when bitten. It could also be that participants failed to separate judgments of loudness from those of pitch, or directed their attention toward other attributes, possibly the previously mentioned subjective measures of hardness or force-to-fracture. However, based on the loudness and amplitude differences reported in Tables 1 and 2 respectively, it is more likely that participants were unable to accurately scale bite sound loudness because the physical differences in terms of water activity were too fine to be easily separated.

The variability of peak frequency values across water activity levels for both snacks likely contributed to the lack of pair-wise differences and does not support Lee et al.'s (1988) contention that low moisture samples output more high frequencies than samples with higher moisture content. Yet, frequency analysis did reveal that tortilla chip bite sounds are characterized by higher frequencies than are Melba toast bite sounds. Peak frequencies of the tortilla chip bite sounds generally are in the 4.0 to 6.0 kHz range, though there was often a broad band of slightly lower amplitude frequencies that extended beyond 12.0 kHz. The Melba toast displayed peaks frequencies between 1.5 and 3.0 kHz but did not show a band of high amplitude frequencies comparable to that seen for the tortilla chip. The data confirm those of Lee et al. (1988) who found characteristic frequencies around 6.0 kHz for tortilla chip and potato chip samples, and Dacremont (1995), who found crispy food sounds to have a higher level of frequencies in the 5.0 to 12.8 kHz range than less crispy or crunchy sounds. Dacremont also reported that crunchy foods were characterized by frequencies in the 1.5 to 2.0 kHz range, similar to that reported here for the Melba toast.

The power spectrum examples in Figures 6 and 7 illustrate some differences between the Melba toast and tortilla chip bite sounds. Figure 6 shows the Melba toast sample to have predominant high intensity frequencies focussed around the single distinct peak at approximately 1.9 kHz. The tortilla chip sounds, as seen in Figure 7, often display a broader range of high intensity frequencies than the Melba toast sounds, with decreasing amplitude extending beyond 12.0 kHz. The tortilla chips' wide band of high intensity frequencies resulted in larger variation among the peak frequencies than that observed for the Melba toast. Since two or more peaks with similar or identical amplitudes were often seen for the tortilla chip sounds, but seldom for those of the Melba toast, the wide range of peak frequencies creates potential interpretive difficulties for the present measure of peak frequency. Consider a tortilla chip bite sound demonstrating two peaks. The lower frequency peak may have a slightly lower amplitude than the subsequent higher frequency peak and it is ignored by the present analysis, even though it may have contributed supplemental information. Such conjecture combined with the lack of peak frequency differences, likely due to the large within sample variation, points to the need for future refinement of the frequency analysis.

The high amplitude and frequencies of the tortilla chips offer support for Vickers (1985) report that with a few exceptions crisper foods typically displayed louder and higher pitched sounds than crunchy foods. While the specific distinction between crispy and crunchy food was not addressed in the present study, the data show a definite frequency difference between the products, perhaps explained by structural analysis of the snacks.

The Pearson correlation matrices revealed few significant relationships between the acoustic and sensory parameters. The lack of pair-wise differences and meaningful correlations involving peak frequency highlights the need for improved frequency characterization, especially to reduce the associated variability. More surprising is the lack of significant correlations between amplitude and crispness for the tortilla chips ($r = .259$, $p = .850$) and Melba toast ($r = .311$, $p = .309$). Other studies, using amplitude measurements different from those used here, have shown larger correlations. Mohamed, Jowitt, and Brennan (1982), for instance, reported a correlation between equivalent sound level (average sound energy) and sensory crispness of $r = .70$, while Seymour and Hamann (1985) used a variety of amplitude measurements and reported correlations no smaller than $r = .81$. However, the latter study considered sound amplitude over limited frequency ranges and not over the range used here.

The relationship between sensory crispness and loudness is well established (e.g., Christensen & Vickers, 1981; Edmister & Vickers, 1985). Using a similar methodology Bisschop (1995) and Boehnke (1996) found crispness and loudness ratings to be highly correlated ($r = .93$ and $r = .99$ respectively). The correlation in the current study is low compared to previous data of Bisschop (1995) and Boehnke (1996) and those of the previously mentioned studies; the high level of control over product moisture content most likely accounts for much of the discrepancy.

The correlation between overall loud and pitch judgments ($r = .555$) was the second largest next only to overall crispness and loudness ($r = .784$) and seems to support Vickers' (1985) report that crisper foods get louder as the pitch increases. However, the present data should be regarded with caution since there is no way to tell if participants detected the simultaneous changes in each attribute, or if the task was too demanding such that they may have had difficulty teasing apart judgments of the two attributes. This is not surprising since few people are aware of the nuances involved in pitch perception. Also, the large correlation ($r = .724$) between pitch and crispness for Melba Toast judgments coupled with the low correlation ($r = .196$, $p > .10$) for tortilla chips toast clearly shows that participants may characterize each snack by different attributes. This is an important distinction that has not been recognized in previous research. The different structural and mechanical properties (e.g., density, average peak force, apparent stiffness) of each snack likely account for the observed differences. Consequently, future research could emphasize the link between material structure and the acoustic stimuli emitted when the material is fractured, preferably with a mechanical force-deformation apparatus similar to that of the human biting mechanism.

The low correlations of pleasantness with the other sensory ratings was unexpected since Bisschop (1995) and Boehnke (1996) each reported pleasantness to be highly related to crispness ($r > .79$) and loudness ($r > .96$). Boehnke also reported a correlation of $r = .93$ between pitch and pleasantness. However, the present data likely are the results of the small intra-product differences between water activity levels. The Bisschop and Boehnke studies used less refined methods to adjust moisture content and therefore produced product moisture contents covering a larger range than the restricted range of water activities (0.0 - 0.43) used in the present study. In isolation the low pleasantness correlations might seem encouraging to the product manufacturers who may want to reformulate their products based on water activity. Since consumers are slow to demonstrate an awareness of product differences caused by altering water levels, manufacturers could investigate near which water activity level consumers begin to rate a product as less pleasant and then change product production accordingly. However, slight increases in water activity can have costly effects on product shelf-life. So, the potential savings from the manufacturing process must be balanced with such potential losses.

When all the attributes rated in the present study are considered, there seems to be a tendency for judges to rate samples on qualities that may be implicit in the general notion of crispness, qualities such as biting force and hardness which are investigated through mechanical analysis.

Mechanical Analysis

Previous studies have investigated mechanical force-deformation measurements and their relationships with both product crispness and consumer acceptance (e.g., Katz & Labuza, 1981; Rohde, Normand, & Peleg, 1993; Seymour & Hamann, 1985; Vickers, 1987). While the present study offers only a cursory examination of these factors, a few interesting informal relationships with sensory and acoustic parameters are noted.

The tortilla chips apparently need greater peak force-to-fracture as water activity increases, indicating that samples become tougher with added water and this observation supports the work of Seymour and Hamann (1985). While a similar observation is made for the Melba toast data, it reverses beyond $a_w = 0.23$, a pattern dissimilar to participant sensory ratings. The apparent stiffness values also appear irregular for each product, with the tortilla chip samples having larger stiffness values than the Melba toast for all but the lowest water activity level. The greater apparent stiffness values of the tortilla chip samples might reflect their dense, thin structure, whereas the Melba toast samples contain more air pockets and thus are less dense. Interestingly, the tortilla chips peak force and amplitude measurements increased as water activity increased, while loudness did the opposite. Although there is no explanation for this discrepancy in tortilla chip loudness ratings, it clearly warrants further study.

The inverse relationship between ratings of tortilla chip sensory crispness and peak force is consistent with the work of Seymour and Hamann (1985), which showed that the hardness or toughness of a product could detract from auditory crispness ratings. Additional support for the notion of mechanical parameters may contribute important information to sensory judgments, is the observation that pleasantness ratings also varied inversely with peak force. It seems, at least for the tortilla chip samples, that participants might, in their sensory crispness and pleasantness ratings, implicitly have included vibro-tactile sensations produced by biting a product. Although these relationships were not formally tested, they follow trends similar to those reported by other researchers (e.g., Christensen & Vickers, 1980; Sauvageot & Blond, 1991; Vickers, 1987) for dry-crisp food products.

Previous research of mechanical parameters and crispness, and the present observations, leads to speculation here that vibro-tactile sensation involved in mastication should be investigated separately from those involved in acoustic perception. The mechanical properties of foods emitting high frequency sounds will be different from those emitting low frequency sounds, with increased stiffness presumably leading to increased frequency of vibration (Vickers, 1987). In addition to the sound produced upon fracture, such vibrations can also be expected to impact the bones and muscles of the jaw and skull, thereby contributing to the sensation of crispness.

Kinesthesis is the sensation of movement, tension, etc. in various body parts received by the nerve ends in muscles, tendons, and joints (Websters, 1988). Such sensations are important in maintaining balance and controlling body movements, including mastication, and function beneath conscious awareness. Yet, this variable has been overlooked in studies of food mastication, despite psychophysical evidence that might point to its potential utility (e.g., Burgess, Wei, Clark, & Simon, 1982). Consequently, it seems that any explanation of mastication related to food crispness or pleasantness should consider the suspected role of vibro-tactile action which should complement the acoustic and mechanical approaches to investigations of crispness already underway.

Participants of the present study commented that, during normal eating, they rarely focus on a particular set of sound attributes and make comparative judgments on them.

By instructing participants to attend to certain attributes and not others, participants' abilities to make ratings based on other attributes, such as the perceived jaw force necessary to bite through a sample, were not assessed; furthermore, casual observation suggests that few people bite snacks in the manner prescribed in this study. However contrived the experimental setup may have been, the study maintained some degree of external validity by using untrained consumers, rather than trained panelists whose responses in studies may be less generalizable.

The present study shows that untrained consumers can scale sensory and hedonic attributes of food sounds using the paired-comparison method. Although the pattern of pair-wise differences and correlations were different for each product, the relationships between loudness and crispness were salient across all ratings. The correlations between loudness and pitch lead to the suggestion that participants might have been unable to clearly differentiate between the two closely related sensory attributes; thus, further research into the role of pitch in food sounds is indicated; such research might include a group of judges, such as musicians, with the proven ability to discriminate pitch, and who also could make judgments regarding timbre which encompasses both amplitude and frequency. In acoustics, timbre is the quality which allows discrimination of middle C (256 Hz) played on a trumpet from middle C played on a saxophone, the relative intensities of particular frequencies differing, depending on the instrument. Other future projects might also involve verifying whether relationships still hold with the improved control over water activity levels for products previously studied by Bisschop (1995) and Boehkne (1996).

The simplification of acoustic analysis enhanced previous findings in showing that sounds emitted from each snack food do differ with respect to amplitude and frequency, and that the simple measures were adequate to demonstrate them. The force-deformation analysis of the snacks supported the notion of mechanical parameters influencing consumers' sensory ratings of crispness and pleasantness, and led to speculation that kinesthetic mechanisms should now be considered for a more thorough description of the sensation of crispness.

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APPENDIX A

Sensory and hedonic means collapsed across water activity levels for each product.

	Product	
Rating	Melba Toast	Tortilla Chip
Crisp	5.403	4.618
Loud	5.103	4.708
Pitch	5.275	5.078
Pleasant	4.918	4.200

APPENDIX B

Repeated Measures Analysis of Variance for Sensory and Hedonic Ratings and Acoustic Measurements.

		F			
Source	df	Crisp	Loud	Pitch	Pleasant
Product	1, 11	20.078*	4.302	0.548	24.575*
a_w	4, 44	6.760*	8.643*	8.387*	9.512*
Product * a_w	4, 44	1.652	4.140*	2.487	2.142

	df	Amplitude	Frequency
Product	1, 11	1.947	51.854*
a_w	4, 40	1.363	1.168
Product * a_w	4, 40	14.454*	1.638

Note. * $p < .05$

APPENDIX C

Summary of ANOVA component and effect size for the main effect of water activity level for two snack foods for sensory and hedonic ratings and acoustic parameters.

	Product					
	Melba Toast			Tortilla Chip		
Attribute	F	MS_{error}	Effect Size	F	MS_{error}	Effect Size
Crisp.	3.243	1.378	0.228	4.885	1.428	0.308
Loud.	3.781	1.248	0.256	8.901	0.830	0.447
Pitch.	6.179	0.833	0.360	2.658	1.245	0.195
Pleasant.	0.658$_a$	1.149	0.056	8.104	1.257	0.424
Amplitude..	18.613	1.5 E-4	0.651	5.139	4.5 E-4	0.339
Frequency..	1.147$_a$	1143850	0.103	1.355$_a$	7574523	0.119

Note. . denotes ANOVA with degrees of freedom = 4, 44.
** denotes ANOVA with degrees of freedom = 4, 40.
$_a$ denotes nonsignificant F with $p = 0.05$.

IMAGE EVALUATION
TEST TARGET (QA-3)

1.0 1.1 1.25 1.4 1.6 1.8 2.0 2.2 2.5 2.8 3.2 3.6 4.0 4.5 5.0

150mm

6"

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