5-2023

Development of an Intervention for Improving Food Acceptance of People with Hearing Loss

Sara Esther Jarma Arroyo
University of Arkansas, Fayetteville

Development of an Intervention for Improving Food Acceptance of People with Hearing Loss

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in Food Science

by

Sara Esther Jarma Arroyo
Universidad de Córdoba
Bachelor of Science in Food Engineering, 2014
University of Arkansas
Master of Science in Food Science, 2016

May 2023
University of Arkansas

This dissertation is approved for recommendation to the Graduate Council.

Han-Seok Seo, Ph.D.
Dissertation Director

Griffiths G. Atungulu, Ph.D.
Committee Member

Andronikos Mauromoustakos, Ph.D.
Committee Member

Suzanne Jervis, Ph.D.
Committee Member

Rachel Glade, Ph.D.
Committee Member

Abstract

Hearing loss, defined as the partial or total inability to hear sound in one or both ears, is the most common sensory deficit in adults to date. Approximately 15% of American adults aged 18 and over report some trouble hearing. The impact of hearing loss may be profound, with consequences for the social, functional, and psychological well-being of the person. Surprisingly, very little attention has been paid on whether auditory loss can significantly impact consumers' sensory perception and overall enjoyment of food. There were four objectives of this dissertation study. Chapter 1 aimed to determine the impacts of hearing loss on the sensory perception and acceptance of solid, and liquid food matrices with various intensities of textural attributes. Chapter 2 was designed to understand the relationships between hearing loss and aroma, flavor and taste perception and acceptance. Chapter 3 aimed to determine the impacts of environmental cues on consumers' with hearing loss perception of their eating environments and food liking and perception in a social dining context. Finally, Chapter 4 aimed to develop an appropriate intervention that improves consumers' with hearing loss overall food acceptance. Results showed that auditory loss impacted the overall acceptance and loudness perception of solid food samples. Pitch intensity was found as a significant negative contributor to the overall liking of solid food samples in individuals with hearing loss. In addition, subjects with hearing loss were not able to discriminate solid food samples with smaller differences in crispness. Loudness perception of liquid foods was also impacted by hearing loss. The group with hearing loss rated liquid samples as less loud compared to the group with normal hearing. No impact of hearing loss was observed on the overall enjoyment of liquid samples. Hearing loss decreased the aroma, flavor perception, and flavor acceptance of applesauce, and orange juice, but little effects were observed on taste perception. Loud external auditory cues negatively impacted the texture liking and flavor perception of food, as well as the general comfort and engagement of subjects with hearing loss during social dining. Finally, a flavor enhanced food product proved to be an appropriate intervention plan to improve individuals with hearing loss overall food acceptance. The outcomes of this dissertation study may offer new strategies for the improvement of the enjoyment of food for consumers with auditory loss. Additionally, this research may motivate the food industry to develop new products for the growing consumer segment that are people with hearing loss.

Keywords: hearing loss, food perception, texture, aroma, flavor, taste, intervention

Acknowledgments

Special thanks to my advisor Dr. Han-Seok Seo. Without his direction, expertise, and constant support over the past four years this work would have not been possible. Thank you to my committee members Dr. Rachel Glade, Dr. Griffiths Atungulu, Dr. Andy Mauromoustakos, and Dr. Suzanne Jervis for their guidance and advice throughout this academic journey.

I would also like to thank my lab mates Asmita Singh (Ph.D. candidate), Lydia Rockers (M.S. student), Victoria Hogan (UASSC manager). You became my second family, and I will be forever thankful for the encouragement and the camaraderie that made our lab such as special place of work.

Last but not less important, I would like to thank my family. Specially, my husband John Kelley, my inspiration for this work and my biggest supporter. Thank you for believing in me even when I did not believe in myself. To my dear mom, your personal sacrifices for my professional growth will never go unnoticed. I am forever indebted to you. Dad, thank you for paving the way for me and for being the best example of professionalism and hard work. Big sister, thank you for encouraging me to be and do better every day, I hope I made you proud.

Dedication

To my loving husband, John, and my baby girl, Olivia Grace.

You make me want to reach for the moon.

Table of Contents

List of Tables

Chapter 3-

Chapter 4-

List of Figures

Chapter 2-

Chapter 3-

Chapter 6-

Chapter 1- General Introduction

Hearing loss is the most common sensory disorder, affecting more than 460 million people worldwide (Goman & Lin, 2016). According to Goman and Lin (2016), approximately 38.2 million Americans (14.3 %) reported some degree of hearing loss, with older individuals (>80 years of age) displaying a higher prevalence and more severe levels of loss. Based on the projections made by the World Health Organization (WHO), the number of people with disabling hearing loss is expected to rise dramatically within the next 50 years due to the aging of the population and the exposure to loud sounds at work (WHO, 2018). This disorder, if untreated, could potentially generate adverse economic costs to society, especially in low-and-middle-income countries (WHO, 2017). From an individual perspective, hearing loss may cause profound impacts on quality of life (QoL), with effects on the social (Dalton et al., 2003), functional (Gates & Mills, 2005; Tremblay & Ross, 2007) and well-being (Heine and Browning, 2002, Monzani et al., 2008) of the person. Higher satisfaction levels on food-related aspects such as diet quality, perceived food satisfaction and eating habits have shown positive correlations with the overall QoL of a wide range of individuals (Jeong & Seo, 2014; Schnettler et al., 2017; Giacalone et al., 2016; Lee et al., 2019). Surprisingly, food-related satisfaction within communities with hearing loss has been largely ignored and very little attention has been paid to whether hearing loss can significantly impact individual's sensory perception of food, food enjoyment, and oral processing of food.

Previous research on the influence of auditory cues on texture perception have shown that sounds emitted by the food during eating can influence the perception on numerous quality (Zampini & Spence 2004; Péneau et al., 2006; Péneau et al., 2007) and textural attributes (Zampini & Spence, 2004; Demattè et al., 2014; Varela et al., 2007). The audible textural properties of solid, semi-solid, and liquid food samples have been demonstrated by acoustic

(Edmister & Vickers, 1985; Zadeike et al., 2018; Çarşanba et al., 2018) and sensory evaluation studies (Zampini & Spence, 2004; Primo-Martin, 2009; Voong et al., 2019;) and a combination of these two approaches (Liu et al., 2015; Roudaut et al., 1998; Andreani et al., 2020). For example, in solid food, Zampini and Spence (2004), demonstrated that the crispness perception of potato chips could be alter by modifying the loudness and/or frequency composition of the auditory feedback elicited during the biting action. In liquid food matrices, beverages also show audible characters that contribute to the perception of attributes such as carbonation (Zampini & Spence, 2005), fizziness (Vickers, 1991; Spence & Wang, 2015) and viscosity (Spence & Wang, 2015). Spence and Wang (2015) found that consumers have the ability to discriminate among pouring sounds of liquids with various viscosity intensities when these were poured in a vessel (Spence & Wang, 2015). The results of these studies also demonstrate that whether consciously or unconsciously, the intrinsic auditory cues of solid, and liquid food contribute significantly to consumer acceptance and overall pleasantness of a product (Drake, 1970; Vickers, 1982). Thus, the absence of auditory feedback that occurs during a hearing loss could negatively impact consumers overall enjoyment and furthermore food-related life satisfaction. The first chapter of this dissertation aimed to determine the impacts of hearing loss on the sensory perception of solid, and liquid food matrices with various levels of sound qualities as perceived by the corresponding textural attributes.

Due to the intrinsic link between some texture attributes and the auditory qualities of food during eating, auditory information also plays a role on the modulation of aroma flavor and taste. In fact, the definition of flavor includes the sounds made during mastication. It is also noteworthy that the insular cortex receives auditory inputs and has been proposed to be involved in the integration of auditory inputs with other sensory systems (Bamiou et al., 2003). A question then arises about how the deficiency of one sense such as hearing, could impact the perception of the chemical senses. The second chapter of this dissertation aimed to determine the impacts of hearing loss on the perception of aroma, flavor, and taste.

Sounds and noise from the environment can also contribute significantly to the perception of food and beverages (Spence et al., 2019). In the United States, complaints about the loud noises in places of public accommodation such as restaurants and bars appears to be on the rise, with some restaurants reaching a volume range of up to 80 dB (Belluz, 2018; Moir, 2015; Spence, 2014). The effects of background noise among hard-of-hearing individuals may be particularly debilitating compared to individuals with normal hearing, affecting aspects such as communication and speech discrimination (Lebo et al., 1994; Valente & Mispagel, 2008; Dawes et al., 2015). In individuals with normal hearing, auditory background can modulate the perception of basic taste, aroma, flavor, and texture attributes of food. More specifically, in terms of textural attributes, crunchiness perception has been found to be intensified under a loud background white noise (around 80–85 dB) (Woods et al., 2011) and the viscosity of liquid samples appears to be suppressed when an auditory block is present (100 dB radio static noise) (Christensen & Vickers, 1981). However, an area that remains unexplored is whether loud background noises impact individuals with hearing loss food perception and enjoyment. The third chapter attempted to answer this question by focusing on the influence of background noise on the food perception and liking of individuals with hearing loss in a more realistic setting (i.e., restaurant).

Chapter 4 of this dissertation aimed to develop an intervention that could potentially ease the effects of hearing loss on food enjoyment and food perception for this segment of the population. Based on the findings from the first three chapters an intervention protocol for individuals with hearing loss was developed. The intervention was based on the five-aspect meal model as a tool to optimize meal consumption (Gustafsson et al., 2006). The meal optimization model states that the improvement of five main aspects: room setting (physical environment), meeting (social company), product (food adapted to meet sensory acceptability), atmosphere (removal of stressful cues) and management control system (organization around the meal) can significantly improve consumers overall enjoyment of food. This model has been previously used by some authors as a tool to improve the experience of a meal in the elderly population (Rothenberg & Wendin, 2015; Song et al., 2016; Sarkar, 2019; Aguilera & Park, 2017; Steele et al., 2015) and it served of great potential for the consumer segment of people with hearing loss. In summary, the objectives of this dissertation are to:

1) Determine the impact of hearing loss on sensory perception and acceptance of food samples varying in crispness and viscosity.
2) Determine the impact of hearing loss on the perception and acceptance of aroma, flavor, and basic tastes.
3) Evaluate the effects of hearing loss on environmental comfort, engagement, food perception and food acceptance during social dining.
4) Develop an interventional strategy to improve individuals with hearing loss sensory acceptability.

References

Aguilera, J. M., & Park, D. J. (2017). Bottom-up approaches in the design of soft foods for the elderly. In M. A. Axelos & M. H. V. d. Voorde (Eds.), *Nanotechnology in Agriculture and Food Science* (pp. 153-166). Wiley. https://doi.org/https://doi.org/10.1002/9783527697724.ch9

Andreani, P., de Moraes, J. O., Murta, B. H. P., Link, J. V., Tribuzi, G., Laurindo, J. B., Paul, S., & Carciofi, B. A. M. (2020). Spectrum crispness sensory scale correlation with instrumental acoustic high-sampling rate and mechanical analyses. *Food Research International, 129*, 108886. https://doi.org/https://doi.org/10.1016/j.foodres.2019.108886

Bamiou, D.-E., Musiek, F. E., & Luxon, L. M. (2003). The insula (Island of Reil) and its role in auditory processing: Literature review. *Brain Research Reviews, 42*(2), 143-154. https://doi.org/https://doi.org/10.1016/S0165-0173(03)00172-3

Barnett-Cowan, M. (2010). An illusion you can sink your teeth into: haptic cues modulate the perceived freshness and crispness of pretzels. *Perception, 39*(12), 1684-1686. https://doi.org/10.1068/p6784

Belluz, J. (2018). *Why restaurants became so loud — and how to fight back. "I can't hear you."* Retrieved January 17 from https://www.vox.com/2018/4/18/17168504/restaurants-noise-levelsloud-decibels

Çarşanba, E., Duerrschmid, K., & Schleining, G. (2018). Assessment of acoustic-mechanical measurements for crispness of wafer products. *Journal of Food Engineering, 229*, 93-101. https://doi.org/https://doi.org/10.1016/j.jfoodeng.2017.11.006

Christensen, C. M., & Vickers, Z. M. (1981). Relationships of chewing sounds to judgments of food crispness. *Journal of Food Science, 46*(2), 574-578. https://doi.org/10.1111/j.1365-2621.1981.tb04914.x

Dalton, D. S., Cruickshanks, K. J., Klein, B. E., Klein, R., Wiley, T. L., & Nondahl, D. M. (2003). The impact of hearing loss on quality of life in older adults. *Gerontologist, 43*(5), 661-668. https://doi.org/10.1093/geront/43.5.661

Dawes, P., Emsley, R., Cruickshanks, K. J., Moore, D. R., Fortnum, H., Edmondson-Jones, M., McCormack, A., & Munro, K. J. (2015). Hearing loss and cognition: the role of hearing AIDS, social isolation, and depression. *PLoS One, 10*(3), e0119616. https://doi.org/10.1371/journal.pone.0119616

Demattè, M. L., Pojer, N., Endrizzi, I., Corollaro, M. L., Betta, E., Aprea, E., Charles, M., Biasioli, F., Zampini, M., & Gasperi, F. (2014). Effects of the sound of the bite on apple perceived crispness and hardness. *Food Quality and Preference, 38*, 58-64. https://doi.org/10.1016/j.foodqual.2014.05.009

Drake, B. K. (1970). Relationships of sounds and other vibrations to food acceptability. In proceedings of the 3rd International Congress of Food Science and Technology Washington, D.C.

Gates, G. A., & Mills, J. H. (2005). Presbycusis. *The Lancet, 366*(9491), 1111-1120. https://doi.org/https://doi.org/10.1016/S0140-6736(05)67423-5

Giacalone, D., Wendin, K., Kremer, S., Frøst, M. B., Bredie, W. L. P., Olsson, V., Otto, M. H., Skjoldborg, S., Lindberg, U., & Risvik, E. (2016). Health and quality of life in an aging population – food and beyond. *Food Quality and Preference, 47*, 166-170. https://doi.org/https://doi.org/10.1016/j.foodqual.2014.12.002

Goman, A. M., & Lin, F. R. (2016). Prevalence of hearing loss by severity in the United States. *American Journal Public Health, 106*(10), 1820-1822. https://doi.org/https://doi.org/10.2105/ajph.2016.303299

Gustafsson, I.-B., Öström, Å., Johansson, J., & Mossberg, L. (2006). The Five Aspects Meal Model: a tool for developing meal services in restaurants. *Journal of Foodservice, 17*(2), 84-93. https://doi.org/https://doi.org/10.1111/j.1745-4506.2006.00023.x

Heine, C., & Browning, C. J. (2002). Communication and psychosocial consequences of sensory loss in older adults: overview and rehabilitation directions. *Disability and Rehabilitation, 24*(15), 763-773. https://doi.org/10.1080/09638280210129162

Jeong, J., & Seo, S. (2014). Importance of satisfaction with food for older adults' quality of life. *British Food Journal, 116*(8), 1276-1290. https://doi.org/10.1108/BFJ-01-2013-0019

Lebo, C. P., Smith, M. F., Mosher, E. R., Jelonek, S. J., Schwind, D. R., Decker, K. E., Krusemark, H. J., & Kurz, P. L. (1994). Restaurant noise, hearing loss, and hearing aids. *The Western Journal of Emergency Medicine, 161*(1), 45-49. https://doi.org/PMCID: PMC1011367.

Lee, J. E., Kim, Y. J., Park, H. J., Park, S., Kim, H., & Kwon, O. (2019). Association of recommended food score with depression, anxiety, and quality of life in Korean adults: the 2014-2015 National Fitness Award Project. *BMC Public Health, 19*(1), 956. https://doi.org/https://doi.org/10.1186/s12889-019-7298-8

Liu, Y., Huang, B.-Z., Sun, Y.-H., Chen, F.-Y., Yang, L., Mao, Q., Liu, J.-S., & Zheng, M.-Z. (2015). Relationship of carrot sensory crispness with acoustic signal characteristics. *International Journal of Food Science & Technology, 50*(7), 1574-1582. https://doi.org/https://doi.org/10.1111/ijfs.12808

Moir, J. (2015). *Why are restaurants so noisy? Can't hear a word your other half says when you dine out? Our test proves restaurants can be a loud as rock concerts.* Retrieved January 17 from http://www.dailymail.co.uk/news/article-3346929/Why-restaurants-noisy-thear-word-half-says-dine-test-proves-restaurants-loud-rock-concerts.html.

Monzani, D., Galeazzi, G. M., Genovese, E., Marrara, A., & Martini, A. (2008). Psychological profile and social behaviour of working adults with mild or moderate hearing loss. *Acta Otorhinolaryngologica Italica, 28*(2), 61-66.

Péneau, S., Brockhoff, P. B., Escher, F., & Nuessli, J. (2007). A comprehensive approach to evaluate the freshness of strawberries and carrots. *Postharvest Biology and Technology, 45*(1), 20-29. https://doi.org/https://doi.org/10.1016/j.postharvbio.2007.02.001

Péneau, S., Hoehn, E., Roth, H. R., Escher, F., & Nuessli, J. (2006). Importance and consumer perception of freshness of apples. *Food Quality and Preference, 17*(1), 9-19. https://doi.org/https://doi.org/10.1016/j.foodqual.2005.05.002

Primo-Martín, C., & Van Vliet, T. (2009). Sensory crispness of crispy rolls: effect of formulation, storage conditions, and water distribution in the crust. *Journal of Food Science, 74*(8), S377-383. https://doi.org/10.1111/j.1750-3841.2009.01318.x

Rothenberg, E., & Wendin, K. (2015). 7 - Texture modification of food for elderly people. In J. Chen & A. Rosenthal (Eds.), *Modifying Food Texture* (pp. 163-185). Woodhead Publishing. https://doi.org/https://doi.org/10.1016/B978-1-78242-334-8.00007-9

Roudaut, G., Dacremont, C., & Meste, M. L. (1998). Influence of water on the crispness of cereal-based foods: acoustic, mechanical, and sensory studies. *Journal of Texture Studies, 29*(2), 199-213. https://doi.org/https://doi.org/10.1111/j.1745-4603.1998.tb00164.x

Sarkar, A. (2019). Oral processing in elderly: understanding eating capability to drive future food texture modifications. *Proceedings of Nutrition Society, 78*(3), 329-339. https://doi.org/10.1017/s0029665118002768

Schnettler, B., Lobos, G., Miranda-Zapata, E., Denegri, M., Ares, G., & Hueche, C. (2017). Diet quality and satisfaction with life, family life, and food-related life across families: a cross-sectional pilot study with mother-father-adolescent triads. *International Journal of Environmental Research and Public Health, 14*(11). https://doi.org/https://doi.org/10.3390/ijerph14111313

Song, X., Giacalone, D., Bølling Johansen, S. M., Frøst, M. B., & Bredie, W. L. P. (2016). Changes in orosensory perception related to aging and strategies for counteracting its influence on food preferences among older adults. *Trends in Food Science & Technology, 53*, 49-59. https://doi.org/https://doi.org/10.1016/j.tifs.2016.04.004

Spence, C. (2014). Noise and its impact on the perception of food and drink. *Flavour, 3*(1). https://doi.org/10.1186/2044-7248-3-9

Spence, C., Reinoso-Carvalho, F., Velasco, C., & Wang, Q. J. (2019). Extrinsic auditory contributions to food perception & consumer behaviour: an interdisciplinary review. *Multisensory Research, 32*(4-5), 275-318. https://doi.org/10.1163/22134808-20191403

Spence, C., & Wang, Q. (2015). Sensory expectations elicited by the sounds of opening the packaging and pouring a beverage. *Flavour, 4*(1), 35. https://doi.org/10.1186/s13411-015-0044-y

Steele, C. M., Alsanei, W. A., Ayanikalath, S., Barbon, C. E., Chen, J., Cichero, J. A., Coutts, K., Dantas, R. O., Duivestein, J., Giosa, L., Hanson, B., Lam, P., Lecko, C., Leigh, C., Nagy, A., Namasivayam, A. M., Nascimento, W. V., Odendaal, I., Smith, C. H., & Wang, H. (2015). The influence of food texture and liquid consistency modification on swallowing physiology and function: a systematic review. *Dysphagia, 30*(1), 2-26. https://doi.org/https://doi.org/10.1007/s00455-014-9578-x

Tremblay, K., & Ross, B. (2007). Effects of age and age-related hearing loss on the brain. *Journal of Communication Disorders, 40*(4), 305-312. https://doi.org/10.1016/j.jcomdis.2007.03.008

Valente, M., & Mispagel, K. M. (2008). Unaided and aided performance with a directional open-fit hearing aid. *International Journal of Audiology, 47*(6), 329-336. https://doi.org/10.1080/14992020801894832

Varela, P., Chen, J., Fiszman, S., & Povey, M. J. W. (2006). Crispness assessment of roasted almonds by an integrated approach to texture description: texture, acoustics, sensory and structure. *Journal of Chemometrics, 20*(6-7), 311-320. https://doi.org/https://doi.org/10.1002/cem.1029

Vickers, Z. M. (1982). Relationships of chewing sounds to judgments of crispness, crunchiness and hardness. *Journal of Food Science, 47*(1), 121-124. https://doi.org/10.1111/j.1365-2621.1982.tb11041.x

Voong, K. Y., Norton-Welch, A., Mills, T. B., & Norton, I. T. (2019). Understanding and predicting sensory crispness of deep-fried battered and breaded coatings. *Journal of Texture Studies, 50*(6), 456-464.

Woods, A. T., Poliakoff, E., Lloyd, D. M., Kuenzel, J., Hodson, R., Gonda, H., Batchelor, J., Dijksterhuis, G. B., & Thomas, A. (2011). Effect of background noise on food perception. *Food Quality and Preference, 22*(1), 42-47. https://doi.org/10.1016/j.foodqual.2010.07.003

World Health Organization (WHO). (2017). *Global costs of unaddressed hearing loss and cost-effectiveness of interventions: a WHO report*. Retrieved January 18 from https://apps.who.int/iris/handle/10665/254659

World Health Organization (WHO). (2018). *Hearing loss is on the rise: Hear the future and prepare for it*. Retrieved January 18 from https://www.who.int/docs/default-source/documents/world-hearing-day-2018-infographic.pdf?sfvrsn=54ccef8d_12

Zadeike, D., Jukonyte, R., Juodeikiene, G., Bartkiene, E., & Valatkeviciene, Z. (2018). Comparative study of ciabatta crust crispness through acoustic and mechanical methods: Effects of wheat malt and protease on dough rheology and crust crispness retention during storage. *LWT, 89*, 110-116. https://doi.org/https://doi.org/10.1016/j.lwt.2017.10.034

Zampini, M., & Spence, C. (2004). The role of auditory cues in modulating the perceived crispness and staleness of potato chips. *Journal of Sensory Studies, 19*(5), 347-363. https://doi.org/10.1111/j.1745-459x.2004.080403.x

Zampini, M., & Spence, C. (2005). Modifying the multisensory perception of a carbonated beverage using auditory cues. *Food Quality and Preference, 16*(7), 632-641. https://doi.org/10.1016/j.foodqual.2004.11.004

Chapter 2 - Literature Review

1. Anatomy of the ear and sound perception in healthy hearing

A peripheral section of the human auditory system is shown in Figure 1. The ear is divided into three main sections: the outer ear, the middle ear, and the inner ear.

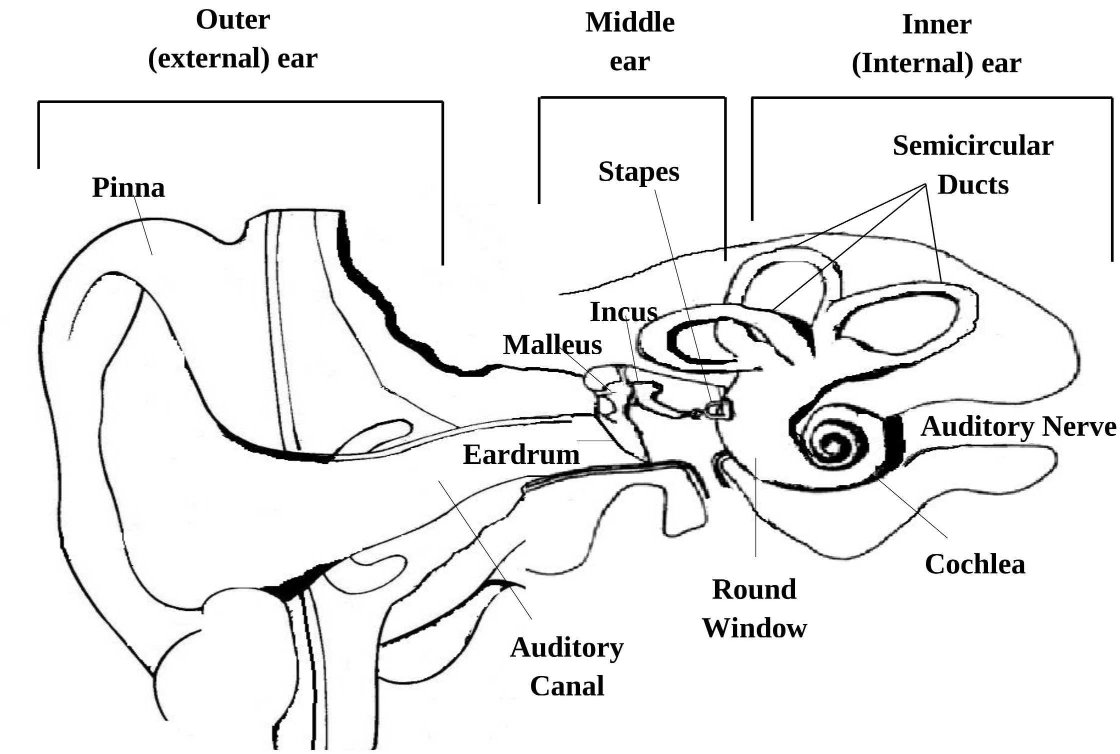

Figure 1. A cross-sectional view of the head showing the anatomy of the human ear.

The outer ear is comprised of the pinna, the auditory canal (or external acoustic meatus), and the eardrum (or tympanic membrane). The pinna is the visible part of the ear, and it is made up of elastic cartilage covered in skin whose main function is to catch sound waves and funnel it down into deeper in the ear (Moore, 2013). Sound waves travel through the auditory canal and cause the tympanic membrane to vibrate. These vibrations are transmitted to the middle ear through three small bones, the ossicles. The middle ear also called the tympanic cavity is the relay station between the outer and inner ear. The main function of the middle ear is to concentrate the pressure of the sound waves, so these are strong enough when entered the inner ear (Moore, 2013). This is accomplished mainly by the difference in effective areas of the eardrum and the oval window, and to a small extent by the lever action of the ossicles. The ossicles are three small bones called the malleus, incus, and stapes, the stapes being the smallest and the lightest of these. One end of the malleus connects to the inner eardrum and moves back and forth when the drum vibrates. The other end of the malleus is attached to the incus which is also connected to the stapes. Together with the form of a chain that conducts eardrum vibrations over to another membrane called the superior oval window (Moore, 2013).

The primary function of the inner is to turn the physical vibrations coming from the middle ear into electrical impulses the brain can identify as sounds (Moore, 2013). The inner ear is composed of the oval window, semicircular canals, and the cochlea. The cochlea is a snail-shell-like structure filled with almost incompressible fluids. This structure is arguably the most important part of the ear since an understanding of the function of the cochlea can provide a key to many aspects of auditory perception (Moore, 2013). The cochlea consists of three main chambers (scala vestibuli, scala media, and scala tympani) that run through it separated by two sensitive membranes, Reisner's membrane, and the basilar membrane. How the basilar membrane vibrates in response to sound is the key to understanding the cochlear function. The tonotopic arrangement of the basilar membrane, which is wider and more flexible at the apical end and narrower and stiffer at the basal end, allows for frequency analysis of sounds. Thus, the basilar membrane responds to high frequencies at its base and low frequencies at its apex (Moore, 2013).

The motion of the traveling wave initiates sensory transduction by displacing the hair cells that sit atop the basilar membrane Because these structures are anchored at different positions, the vertical component of the traveling wave is translated into a shearing motion between the basilar membrane and the overlying tectorial membrane. The tectorial membrane is a gelatinous structure that lies above the stereocilia. The stereocilia of the outer hair cells come in contact with the tectorial membrane, so that, when the basilar membrane moves up and down, a shearing motion is created between the basilar membrane and the tectorial membrane. As a result, the stereocilia at the tops of the hair cells are displaced leading to voltage changes across the hair cell membrane.

Sound perception, as assisted by the ear as the organ of hearing, may not be described without a characterization of the physical nature of sound. Sounds originate from the vibration of an object which in turn generates pressure waves that transfer the vibration to the molecules in a medium (generally air). Sound waves have four major features: waveform, phase, amplitude (usually expressed in log units known as decibels, abbreviated dB), and frequency (expressed in cycles per second or Hertz, abbreviated Hz). For humans, the amplitude and frequency of sound pressure correspond to loudness and pitch, respectively (Kinsler & Frey, 1962). Visualization of a sound waveform is achieved by plotting the sound amplitude against time. The simplest form of soundwaves are called sinusoids, also referred to as pure tones (Figure 2).

Pure tones, like that of a tuning fork, are rare in nature. Most sounds, such as those from speech, consist of acoustically complex waveforms that are often modeled as the sum of sinusoidal waves of varying amplitudes, frequencies, and phases. The human ear automatically and involuntarily performs a transformation that converts the complex waveforms into a spectrum, a description of the sound as a series of volumes at distinct pitches. The brain then turns this information into a perceived sound. A similar conversion can be done using mathematical methods on the same sound waves or virtually any other fluctuating signal that varies with respect to time by a mathematical tool denominated Fourier transform (Bracewell, 1989).

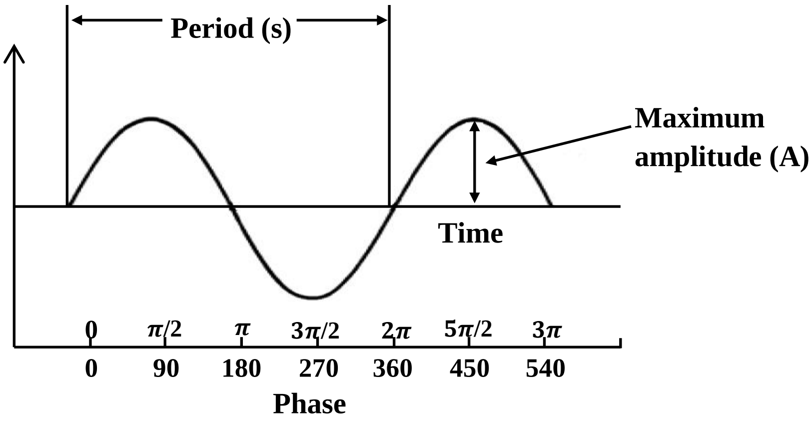

Figure 2. The waveform of a sinusoidal vibration. Only l.5 cycles are shown. The phase may be measured in degrees or radians. One complete cycle corresponds to 360° or 2n radians.

1.1.The mechanoelectrical transduction of sound waves

Mechanoelectrical transduction is mediated by the inner hair cells. The hair cell is a flask-shaped epithelial cell named for the bundle of hair-like processes that protrude from its apical end into the scala media (Purves et al., 2004; Bracewell, 1989). The filamentous structures that connect the tips of adjacent stereocilia, known as tip links, open cation-selective transduction channels when stretched, allowing K+ ions to flow into the cell altering the voltage difference between the inside and outside the hair cell. This, in turn, leads to a release of neurotransmitters and the initiation of action potentials (or pulses) in the neurons of the auditory nerve (Purves et al., 2004). The great majority of afferent neurons (around 95%), which carry information from the cochlea to higher levels of the auditory system, connect to inner hair cells. Thus, most of the information about sounds is conveyed via the inner hair cells. Auditory nerve fibers could be classified into three groups based on their spontaneous rates. About 61 % of fibers have high spontaneous rates (18-250 pulses per second); 23% have medium rates (0.5-18 pulses per second); and 16% have low spontaneous rates (less than 0.5 pulses per second) (Moore, 2013). The threshold of a neuron is the lowest sound level at which a change in response of the neuron can be measured. High spontaneous rates tend to be associated with low thresholds and vice versa. The most sensitive neurons may have thresholds close to 0 dB SPL, whereas the least sensitive neurons may have thresholds or 80 dB SPL or more (Liberman, 1978).

1.2. Neural pathways in the auditory system

The auditory nervous system consists of ascending and descending pathways that connect the ear with the auditory cerebral cortex. The ascending projections of the auditory brainstem have a high degree of bilateral (both sides) connectivity, which means that damage to central auditory structures is rarely manifested as a hearing loss (Purves et al., 2004). In the classical auditory ascending pathway, type I auditory nerve fibers carry signals from inner cells in the cochlea to the ipsilateral (same side) neurons in the first relay nucleus (the cochlear nucleus, CN) located in the brainstem. Binaural inputs that arise from the right and left anteroventral CN go to the superior olivary complex (SOC). SOC is the first group of nuclei that integrate information from both ears. The nuclei of the SOC are involved in directional hearing, mainly by comparing the arrival time of neural activity form the two ears and intensity differences (Purves et al., 2004; Bracewell, 1989).

A second major set of pathways from the CN bypasses the SOC and terminates in the nuclei of the lateral lemniscus (LL) on the contralateral side of the brainstem. These particular pathways process other temporal aspects of sound, such as duration. Auditory pathways ascending via the MSO and LL, as well as other projections that arise directly from the CN, project to the midbrain auditory center, to the inferior colliculus (IC). The IC has the ability to process sounds with complex temporal patterns (Purves et al., 2004; Bracewell, 1989). Many neurons in the IC respond only to frequency-modulated sounds, while others respond only to sounds of specific durations. Such sounds are typical components of biologically relevant sounds, such as those made by predators, or intraspecific communication sounds, which in humans include speech. Fibers from the ICC project to the medial geniculate nucleus (MGN) in the thalamus. Neurons in the MGN receive convergent inputs from spectrally and temporally separate pathways, mediating the detection of specific spectral and temporal combinations of sounds. Finally, as the ultimate target of afferent auditory information the fibers from the MGB project to the primary auditory cortex (AI). The AI is located on the superior temporal gyrus in the temporal lobe, and it contains a topographical map of the cochlea. Although the sensory processing that arises in the auditory cortex is not well understood, they are likely to be important to higher-order processing of natural sounds, especially those used for communication. Sounds that are especially important for intraspecific communication often have a highly ordered temporal structure. In humans, the best example of such time-varying signals is speech, where different phonetic sequences are perceived as distinct syllables and words. Studies of human patients with bilateral damage to the auditory cortex also reveal severe problems in processing the temporal order of sounds (Purves et al., 2004). It seems likely, therefore, those specific regions of the human auditory cortex are specialized for processing elementary speech sounds, as well as other temporally complex acoustical signals, such as music (Purves et al., 2004).

2. Hearing disorders: types and degrees of severity

Hearing loss is defined as the partial or total inability to hear sound in one or both ears. When describing hearing loss, three aspects are primarily looked at the type of hearing loss, degree of hearing loss, and configuration of hearing loss (ASHA, 2019). There are two main types of hearing loss: conductive hearing loss and sensorineural hearing loss. Conductive hearing loss (CHL) occurs when there is a problem, usually in the outer and/or middle ear, that obstructs the transmission of sound to the cochlea. Conductive hearing loss causes soft sounds difficult to hear and louder sounds been muffled. There is a wide range of causes of conductive hearing loss including fluid in the middle ear from colds or allergies; middle ear infection (otitis media); poor eustachian tube function (the tube that connects the middle ear and nose); hole in the eardrum; excess of earwax (cerumen); infection in the ear canal (external otitis); foreign body in the outer ear; or a malformation of the outer ear, ear canal, or middle ear. This type of hearing loss can often be corrected medically or surgically (Eggermont, 2017). Sensorineural hearing loss (SNHL), the most common type of permanent hearing loss, occurs when there is damage to the inner ear (cochlea) or the nerve pathways from the inner ear to the brain (Eggermont, 2017). If the loss is preneural it is called sensory loss, if it is neural, it is called neural loss. However, a sensory loss may lead to neural loss, and differentiating the two may become impractical, hence sensorineural is often appropriate. Most of the time, SNHL cannot be medically or surgically corrected but can be managed with assistive devices (Eggermont, 2017).

The severity of the hearing loss is classified according to ranges of nominal thresholds in which a sound must be so it can be detected by an individual. It is measured in decibels of hearing loss, or dB HL. The measurement of hearing loss in an individual is conducted over several frequencies, mostly 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz. The hearing loss of the individual is the average of the hearing loss values over the different frequencies. Clark (1981) classified hearing loss severity according to the frequency of nominal thresholds measured in decibels in hearing level (dB HL) as follows: normal (-10 to 15 dB HL), slight (16 to 25 dB HL), mild (26 to 40 dB HL), moderate (41 to 55 dB HL), moderately severe (56 to 70 dB HL), severe (71 to 90 dB HL), and profound (91+ dB HL).

2.1 Causes of acquired hearing loss

The most common causes of acquired hearing loss include age, noise exposure, head trauma, virus or disease, genetics, and ototoxicity (ASHA, 2019). Age-related hearing loss constitutes one of the most frequent sensory problems in the elderly (Bagai et al., 2006). Approximately, 30% of those ages 65 and older, more than 50% of those over the age of 75 present hearing loss (Jee et al., 2005). Presbycusis (hearing loss associated with aging) is typically gradual, bilateral, and characterized by high-frequency hearing loss (Bagai et al., 2006). Damages in the hair cells and the auditory nerves due to genetic and environmental factors such as smoking and exposure to loud noises are proposed to be the basis of presbycusis (Schuknecht, 1955). Thus, Eggermont (2017) referred to presbycusis as an accumulation of auditory stress during a lifetime. However, there is evidence that the exposure of environmental stressors alone may not be the only cause of hearing loss in elders. Sergeyenko et al. (2013) observed age-related cochlear synaptic and neural degeneration in mice never exposed to high-level noise. Additionally, Viana et al. (2015) demonstrated that synaptopathy and the degeneration of cochlear nerve peripheral axons, despite a near-normal hair cell population, may also play an important role in presbycusis for adults aged 54-89 years, without any history of otologic disease. Various authors have also pointed to changes in the central auditory system by magnetic resonance spectroscopy (MRS) and by functional MRI (fMRI) in the aged brain. However, Humes et al. (2012), argues that changes in the auditory cortex are not an isolated unit, but rather a snowball effect of the changes in the inner ear.

Noise-induced hearing loss (NIHL) is another major cause of acquired hearing loss (Eggermont, 2014). Excessive environmental noise levels are known to contribute to NIHL. Worldwide, 16% of disabling hearing loss in adults is attributed to occupational noise exposure, ranging from 7% to 21% in various regions of the world (Nelson et al., 2005). Regulations of the National Institute for Occupational Safety and Health (NIOSH) limit the level of daily noise exposure in the workplace (NIOSH, 1996). Overall, a noise level of Leq 1 h= 105 dB(A) is currently accepted as traumatic, which is inducing a permanent hair cell loss, and up to Leq 8 h=80 dB(A) is safe for the auditory system over a lifetime (Eggermont, 2014). The auditory injury threshold is the lowest level capable of producing any permanent threshold shift (PTS), regardless of exposure time. The auditory injury threshold can be expected between approximately 75 and 78 dB(A) (Mills et al., 1981; Nixon et al.,1977). However, a recent study by Norena et al. (2006), showed that a 4-month exposure of adult cats to a 4-20 kHz band-pass sound presented at 76 dB(A) did not result in auditory brainstem response (ABR) threshold changes compared to controls. Norena et al. (2006) also showed changes in the tonotopic map in the primary auditory cortex, resulting from a strongly reduced sensitivity of cortical neurons to frequencies between 4 and 20 kHz, and enhanced responsiveness at frequencies below and above that frequency range.

2.2 Strategies to manage hearing loss

Hearing aids (HA) are small electronic devices that amplify and alter the sound to make-up for damaged parts of the ear. HA are prescribed for individuals with SNHL rather than with CNHL. According to Chien and Lin (2012), in the United States, only about 14.2% of the population with hearing loss 50 years old or older wear HA’s. Kaplan-Neeman et al. (2012)

found that excessive amplification of background noise, low functionality, and high costs where the main reasons adults with hearing loss will not wear a HA.

Even though many authors have demonstrated that HA's devices can significantly improve the quality of life of individuals with hearing loss (Kitterick & Ferguson, 2018; Humes et al., 2017; Abrams et al., 2005; Mulrow et al., 1990), it is important to mention that these devices do not fully restore the sense of hearing since they cannot replace the nonlinear amplification quality natural from the cochlea (Eggermmont, 2014). Additionally, most HAs are not able to provide accurate signal-to-noise ratios (SNR's) that allow speech understanding with background noise. The speech-reception threshold (SRT) is defined as SNR at which 50% of two-syllable words are repeated correctly by the listener when background noise is present. The SRT of people with hearing loss may be as high as 30 dB compared with that of people with NH. This means that for given background noise, the speech needs to be as much as 30 dB higher for people with hearing loss to achieve the same level of understanding as people with NH (Chung, 2004). Kidd et al. (2015) proposed algorithms that implement environmental noise reduction attenuating unwanted sound sources to improve SNR's. Kidd et al. (2015) also emphasize strategies that HA manufacturers could implement with regards to directional amplification, which highlight a specific source of sound related to the listener's head improving SNR and enhancing source selection. However, the authors warn that even though these strategies are useful in reducing unwanted sounds, they alone are not able to help the listener in choosing among competing speeches. Thus, factors such as cognition and attention in individuals with hearing loss are always important and should be prioritized (Kidd et al., 2015).

Cochlear implants (CI's) are another alternative for individuals with hearing loss improve their hearing quality and understand speech. A CI tries to replace the function of the inner ear by turning sound into electrical energy. This energy can then be used to stimulate the cochlear nerve, sending "sound" signals to the brain. Individuals who are deaf or with severe to profound hearing loss may be candidates to a CI fitting. In the United States, approximately 58000 devices have been implanted in adults and 38000 devices in children (FDA, 2012). CI's consist of essentially three parts: an external sound processor, a subcutaneous receiver, and an intracochlear electrode array. Sound is picked up by the external sound processor worn near the ear. The sound processor splits the sound in up to 120 channels by band-pass filtering. This sound is sent to a speech processor, which is most often connected to the microphone and worn behind the ear. The sound is analyzed and converted into electrical signals, which are sent to a surgically implanted receiver behind the ear. This receiver sends the signal through a wire into the inner ear. From there, the electrical impulses are sent to the brain (Eggermont, 2017). Wie (2010) showed that when children receive a cochlear implant followed by intensive therapy before they are 18 months old, they are better able to hear, comprehend sound and music, and speak than their peers who receive implants when they are older. Bat-Chava and Deignan (2001) focused on how parents with deaf children describe their children's communication skills and peer relationships before they had the implant and afterward. According to parents' reports, Bat-Chava and Deignan (2001) found that the cochlear implant offered deaf children opportunities for improved social relationships. Specifically, the implant can improve the children's hearing and speech, and, because of these improvements, it also has the potential to change the children's personality or increase their level of confidence.

2.3 Impacts of hearing loss in quality of life

As with any other sensory deficiency, the implications of having a hearing loss on the quality of life (QoL) of the individuals that experience this disorder are considerable. Dalton et al.

(2003) investigate the impact of hearing loss on QoL in the older population. Health-related quality of life was assessed by using measures of activities of daily living (ADLs), instrumental ADLs (IADLs), and the Short Form 36 Health Survey (SF-36). Dalton et al. (2003) found that the severity of hearing loss was significantly associated with having a hearing handicap and with self-reported communication difficulties. Individuals with moderate to severe hearing loss were more likely than individuals without hearing loss to have impaired ADLs and IADLs. The severity of hearing loss was significantly associated with decreased function in both the mental component score and the physical component score of the SF-36. Similarly, Gopinath et al. (2012), found negative correlations between hearing loss and the mental component score of the SF-36 in a longitudinal 10-year study. Gopinath et al. (2012) also found that using assistive devices such as hearing aids showed a 1.82-point and 3.32-point increase in SF-36 mental composite score and mental health domain over the 10-year follow-up, respectively. Carlsson et al. (2014) evaluated mental health-related QoL of 2139 participants with severe and profound hearing loss by using the Hospital Anxiety and Depression Scale questionnaire. Carlsson et al. (2014) found greater levels of anxiety and depression among patients with severe or profound hearing loss as compared to the general population. Additionally, the author found that annoying tinnitus and vertigo had strong negative effects on QoL.

3. Sound and its impacts on the perception of textural attributes of food: product-intrinsic contributions

Sounds emitted by opening a food package (Spence & Wang, 2015; Spence & Zampini, 2006; Wang & Spence, 2019), during food preparation, or during food consumption (Christensen & Vickers, 1981; Zampini & Spence, 2004; Zampini & Spence, 2005) have been found to influence the perception of numerous sensory and quality attributes of what is being eaten. The body of research focused on the contribution of sounds to the textural perception of food often takes one of two approaches: 1) contribution of sounds elicited during mastication or swallowing of food and beverages to the sensory perception of the product (product-intrinsic contributions) 2) changes on sensory perception of food as influenced by background music and sounds (product-extrinsic contributions). In this section, the first approach that focuses on the product's intrinsic contributions will be reviewed.

3.1 Perception of air and bone-conducted sounds during eating

The noises perceived during the sensory evaluation of foods are transmitted to the inner ear through two routes: (a) the middle ear (tympanic membrane and the ossicular chain), and (b) bone conduction. Bone conduction is referred to the transmission of sound to the inner ear primarily through the bones of the skull, allowing an individual to perceive sounds bypassing the ear canal (Kinsler & Frey, 1962). Drake (1965) measured and analyzed the amplitude-time plots elicited by chewing some food products (i.e., beef, crispbread, apple, lettuce, and peanuts) through three methods: through cheek (microphone was attached against the cheek), open mouth (microphone was placed 2 in front of the open mouth while the subject chewed the sample between the front teeth), and ear canal (microphone was attached to the participant's ear canal). Drake (1965) found that bone generally conveys lower-frequency sounds better due to the absorption of sound by the soft tissue of the mouth and by the jaw. Some authors found that the resonance frequency of the mandible is 160 Hz and that sounds generated at this frequency are amplified when chewing with a closed mouth (Vickers & Bourne, 1976; Kapur, 1971). Similarly, Dacremont et al. (1991) studied the contributions of both air and bone conduction sounds during the sensory evaluation of six food products with crunchy, crackly, and crispy textures. The authors found that the eating technique that the panelists used (bite or chew) modified the contribution of air-and bone-conduction to auditory sensation. Dacremont et al. (1991) reported that to match what is heard during the consumption of a product, bone-conduction sounds had to be attenuated over the frequency range of the mandible (160 Hz) and that the air-conduction sounds have to be attenuated at a frequency range around 160 Hz and amplified at a frequency range around 3,500 Hz to match the action of the middle-ear muscles which behave differently when sounds were generated inside or outside the mouth (Dacremont et al., 1991).

3.2 Solid food matrices: auditory crispness

Assessments associated with the auditory components of the crispiness of solid food matrices have been demonstrated in the literature utilizing sensory studies, acoustic evaluations, and the relationships that exist between these two measurements. Consumer sensory research conducted by Szczesniak (1988) showed that crisp food may be defined as one that is firm, snaps easily, and emits a crunchy/crackly sound upon deformation. Christensen and Vickers (1981) found relationships between biting and chewing sounds and judgments of food crispness. In Christensen and Vicker's (1981) study, subjects separately judged the loudness of chewing sounds and the crispness of a wide range of wet and dry crisp foods. Judgments of perceived crispness and loudness were highly correlated both when food samples were fractured by single bites and when further broken down by chewing (Christensen & Vickers, 1981). It is important to highlight that Christensen and Vickers (1981) employed an ‘oral methodology’ (i.e., consumers evaluated the sound and textural characteristics of samples while they chew or bite the sample) to demonstrate the previously mentioned relationships. Another methodology that is employed in food acoustic research is an ‘auditory methodology’, where prerecorded sounds are played during the subject evaluation of the samples. Zampini and Spence (2004) used an auditory approach to demonstrate that the perception of the crispness and staleness of a food product can be affected by varying the loudness and/or frequency composition of the auditory feedback elicited during the biting action. The potato chips used as food samples by Zampini and Spence (2004) were perceived as being both crisper and fresher when either the overall sound level was increased, or when just the high-frequency sounds (in the range of 2 kHz−20 kHz) were selectively amplified. In a similar study, Demattè et al. (2014) manipulated the sound produced while biting into apple samples. Participants rated the perceived crispness of three apple cultivars: 'Renetta Canada', 'Golden Delicious', and 'Fuji' while hearing a veridical sound without any frequency adjustment (0 dB filter) or with high frequencies attenuated (either by −12 dB or by −24 dB) when biting into the apple. The authors found that perceived crispness was significantly lower when any of the reductions were applied than when no filter (0 dB) was used. However, perceived hardness was significantly affected by the sound information as well: Hardness was rated as being significantly lower when a global sound reduction was applied than when the sound was unfiltered (Demattè et al., 2014).

Acoustic recordings have also been employed as a method to further study the crispness of solid food matrices. The plots produced by recording the sounds made during the mastication of crisp products have been characterized by determining the maximum amplitude, the number of peaks, the mean height of the peaks, and the duration of the sound. Drake showed that the amplitude of the sound produced during biting of toasted bread increased as the degree of toast increased; a higher toast level produced a crisper product. From this, it was inferred that the higher the amplitude of the amplitude–time plot, the crisper the toast. Frequency and duration of sound were not as important as amplitude as a measure of the crispness of toast (Drake, 1963). However, Edmister and Vickers (1985) concluded that a combination of the mean height of the peaks x the number of peaks is a better predictor of crispness for dry and wet crisp foods than other parameters such as the number of sound bursts, duration, mean height peaks x number of sound bursts, mean height peaks x number of sound bursts/thickness.

The Fast Fourier Transform (FFT) method is used to characterize the most evident frequencies during biting and chewing of foods. Comparison of the predominant frequencies resulting from biting and chewing crisp, crunchy, and crackly is possible with FFT. Dacremont, (1995) found that a large volume of bone conduction is evident when eating crispy foods and absent when eating crunchy foods. Consumption of crispy foods is characterized by sound with frequencies greater than 2 kHz (Dacremont, 1995). Even though the use of acoustic determinations is important for the appreciation of crispness, in foods, the use of a combination of acoustic and sensory science may potentially improve the understanding of the perceptions evolving from biting or chewing crisp, crunchy, and crackly foods (Duizer, 1998).

3.2.1 Physical properties of solid food matrices with an auditory component

The physical structure of food has a large influence on the sounds produced when biting into products. In the case of solid food matrices, the sound emitted by foods depends on the macroscopic (length, width, and thickness) and microscopic characteristics (arrangement of the cells, chemical bonds, impurities, and existing cracks) within the food (Chakra et al., 1996). The cellular composition has been pointed out as one of the most relevant microscopic properties with regards to the product sound emission. More specifically, products that contain fluid within their cells, such as apples, are termed wet crisp products, while cellular products containing only air within their cells, such as cheese balls or potato chips are termed dry crisp products (Jowitt, 1974). Although wet crisp and dry crisp products differ in cellular composition, Edmister and Vickers (1985) found that there is no difference in the perception of crispness between the two products. Both foods produce similar auditory cues for the perception of crispness to occur

(Edmister & Vickers, 1985). There is less known about the effects of macroscopic structure on sound production. Sound emission during biting appears to change as the sample dimension (length, width, and thickness) of the product changes (Chakra et al., 1996). Bruns and Bourne (1975) showed that the force required to snap a uniform cross-section of a rectangular food sample was directly proportional to the width and of the square thickness. In other words, if the samples are evaluated within a reasonable similar dimension, their texture perception should be the same (Duizer, 1998).

3.3 Liquid food matrices auditory components

The audible textural properties of semi-solid and liquid food have been less explored than that of the crispness, crackliness, and crunchiness of solid matrices. Previous studies have focused on the auditory cues that occur when a beverage is poured from the packaging into some form of receptacle or vessel, such as carbonation, fizziness, and temperature (Vickers, 1991; Wang & Spence, 2015; Zampini & Spence, 2005). Vickers (1991) suggested that the sounds of "fizziness" produced by certain fine champagnes might have particular characteristics, such as higher-pitched fizz produced by the smaller bubbles. Zampini and Spence (2005) conducted a series of experiments to demonstrate that the perceived (or rated) carbonation of a cup of sparkling water that was held in the hand could be modified simply by boosting either the loudness of the popping sounds (boosting sounds in the 2–20 kHz range by 20 dB) or the speed at which the bubbles were heard to pop in the cup. Additionally, Velasco et al. (2013) demonstrated that consumer can discriminate between hot or cold water based on the sounds that the liquids made during pouring. In this study, the authors recorded sounds of water being poured into cups of different materials such as glass, porcelain, and paper were recorded. The water, in this case, came either from a kettle that had just been boiled or else from a jug of water that had been sitting for a while in the fridge (82–84 °C or 6–8 °C, respectively). These sound files were then played back to a group of participants who answered more than 70 % of their forced-choice decisions correct when it came to discriminate between the sound of hot and cold water (Velasco et al., 2013). In terms of the sound of textural attributes in beverages, it has been suggested that the viscosity of liquids may have an audible character. Spence and Wang (2015) tested consumers' ability to discriminate between liquids of different viscosities. The participants typically heard one of three pouring sounds, associated with water, water with 25 % sugar by weight added and water with 50 % sugar by weight added and had to rate on two seven-point scales how “thick and sticky” (with 7 being most sticky) and how pleasant the pouring sounds were. In this study, people were able to discriminate the difference in viscosity based on sound alone (Spence & Wang, 2015). Additionally, the same authors explored the effect of alcohol content of wine, as an indication of viscosity, on the discrimination of the samples by pouring recordings. Based on the notion that lower alcohol levels produced lower levels of viscosity, Spence and Wang (2015) used low-alcohol white wine and high-alcohol red wine for the discrimination task. Participants had to answer four questions (testing the sounds of pouring into both red and white wine glasses, with both orders of sound presentation). The participants answered more questions correctly (99/172) than expected by chance (86/172). This research demonstrated that consumers could discriminate subtle differences in viscosity as well as the more noticeable ones such as water and honey (Spence & Wang, 2015). More recently, Pellegrino et al. (2019) in a study designed to compare and contrast the sensitivity of humans to changes in viscosity through different sensory modalities discovered that oral tactile and audition proved to be the most sensitive modalities to changes in viscosity. Pellegrino et al. (2019) employed Iota-carrageenan (IC) to thicken milk at several concentrations, ranging from 0.00% to

0.111% (w/v). For the auditory stimuli, the authors presented two recordings on a screen allowing the individual to play the sound of each (at 70 dB through headphones) and then choose the thicker sounding clip. It is critical to highlight that the previously mentioned studies looking into the effects of sound on viscosity focused on the effects of pouring sounds (auditory approach) and did not look into the potential of oral sensations (oral approach).

Due to a decrement on swallowing and chewing abilities with age, semi-solid food products, and their sound-textural characteristics have been explored generally in the context of texture-modified diets for nurse care. Endo et al. (2016) described that one of the most commonly mentioned issues on the acceptability of pureed or semi-solid foods within the elder population is the texture or therefore lack. The authors suggested that for semisolid food matrices the presentation of virtual chewing textural-sounds could be employed as a means to improved nurse-care food acceptability (Endo et al., 2016). Endo et al. (2016) investigated whether altered auditory feedback of chewing sounds generated using electromyogram (EMG) of the masseter could alter the perceived sensations of nursing care foods even if the actual food texture were dull. The frequency properties of the EMG signal were modified to be heard as a crunchy sound, much like that emitted by chewing, for example, root vegetables (Endo et al., 2016). Healthy participants rated the taste, texture, and evoked feelings of five kinds of nursing care foods under two conditions (with/without the EMG chewing sound). Nursing care foods were perceived as stiffer and rougher with the presentation of crunchy virtual chewing sounds. Moreover, foods were perceived to have a greater number of ingredients, and satisfaction and pleasantness were also greater. Thus, considering the effect of altered auditory feedback while chewing, we can suppose that such a tool would be a useful technique to help people with texture-modified diets to enjoy their food (Endo et al., 2016). In a follow-up study, Endo et al. (2017) examined the influences of texture inhomogeneity on the effects of chewing sound modulation. Three kinds of nursing care foods in two food process types (minced-/pureed-like foods for inhomogeneous/homogeneous texture respectively) were used as sample foods. In this study, healthy elderly participants rated the taste, texture, and evoked feelings in response to sample foods under two conditions with and without the pseudo-chewing sound (by using EMG frequency signals). The results regarding the effects of the pseudo-chewing sound, sowed that taste was less influenced, and that the perceived food texture tended to change in the minced-like foods, and evoked feelings changed in both food process types (Endo et al., 2017).

4. Influence of extrinsic auditory cues on texture perception of food: product-extrinsic contributions

Another approach to the contribution of sounds to the textural perception of food is related to how sensory perception of food is influenced by background noise and sounds (product-extrinsic contributions). Within this context, the literature refers to 'noise' as unwanted sounds known to be unpleasant, loud, or disruptive to the food tasting experience (Spence et al., 2019). Complaints about noise in restaurants and bars appear on the rise in the past years (Belluz, 2018; Moir, 2015; Spence, 2014). This is one of the main reasons that have motivated researchers to understand the effects of noise on consumer sensory perception of food. For example, using a range of typical snack foods such as Pringles Original Salted Crisps and Sainsbury's Nice Biscuits, Woods et al. (2011) investigated the effects of auditory background noise on the perception of taste qualities (sweetness, saltiness), and crunchiness. Woods et al. (2011) reported that sweetness and saltiness were significantly lower in the loud compared to the quiet sound conditions. However, crunchiness perception was intensified under the loud background white noise (in this case, presented over headphones at around 80–85 dB). Woods et al. (2011)

suggest that food properties unrelated to sound (sweetness, saltiness) and those conveyed via auditory channels (crunchiness) are differentially affected by background noise (Woods et al., 2011). Contrastingly, Christensen and Vickers (1981) did not find that background noise (100 dB radio static continuous noise via headphones) affected crispness perception. Concerning liquid food, Christensen, and Vickers (1981) found that viscosity perception is affected by background noise. Subjects in Christensen and Vickers (1981) study judged the viscosity of a series of thickened aqueous solutions (1, 3, 9, 27, 81, 243, 729, and 2187 centipoises) under an auditory block condition (100 dB static FM radio noise via headphones) and a no block condition (no headphones worn during the judgment). The authors found that consumers rated the viscosity of the samples lower when the auditory block was used. However, a high correlation was found between the auditory block and the no block conditions viscosity scores indicating that consumers were still able to discriminate between the various levels of viscosity (Christensen & Vickers, 1981).

For individuals with hearing loss background noise can be particularly debilitating. Although persons with normal hearing do experience hearing difficulties in restaurants, the inability to understand speech in noisy restaurants can become so frustrating to individuals with hearing loss that many of them tend to avoid outside dining and social activities (Lebo et al., 1994). Mosher and Jelonek (1991) employed the 'Patient Satisfaction Survey' for adults with hearing loss to identify difficult listening environments and important listening situations. The results of this survey indicate that more than 80% of this group is dissatisfied with its ability to hear and understand conversations in restaurants, both with and without hearing aids. Most of the research on this area has focused on the effect of various hearing aids technologies on speech discrimination when background noise is present (Lebo et al., 1994; Valente & Mispagel, 2008;

Dawes et al., 2015). However, no research has focused on how background noise affects adults with hearing disorders food perception, and food enjoyment.

5. Relationships between sound-texture and mastication and swallowing behaviors.

Jaw-muscle, tongue, and facial muscle activity generated by the mastication process are adapted in response to sensations derived from the changing properties of the food as it is chewed (Kohyama et al., 2007). These, mainly texture-related, sensations guide mastication up to the point that a bolus is formed that can be safely swallowed. It has been also demonstrated that oral processing of solid foods varies with the type of sensory judgment (Gonzalez et al., 2004). Chewing of crispy food involves jaw deceleration and acceleration as a result of resistance and breakage of food particles, and a characteristic sound of the breakage of the food particles is produced (Van Der Bilt et al., 2010). The breakage behavior of food and the corresponding sound is essential for the sensory sensation. Van Der Bilt et al. (2010) measured the chewing behavior (via skull vibration) of subjects while they chewed and swallowed three crispy foods (biscuits) and one non-crispy food (cake). The authors observed that skull vibrations generated during the chewing of crispy food gradually decreased as a function of the number of chewing cycles. Just before the moment of swallowing, the levels of skull vibration produced by chewing the crispy samples had reached the low level produced by a non-crispy food (cake). At that moment, the crispy biscuits had been chewed long enough to form a well-moistened food bolus that was ready for swallowing (Van Der Bilt et al., 2010). Similarly, Van Der Bilt et al. (2011) explored the influence of auditory information on the neuromuscular control of chewing crispy food. In this study, participants chewed biscuits of three different levels of crispness under four experimental conditions: no masking, auditory masking (loud sounds via headphones), visual masking, and auditory plus visual masking. Skull vibration, jaw-muscle activity, and jaw movement were measured via EMG while the subjects chewed and swallowed the food. Auditory and/or visual masking did not have a significant effect on skull vibration, muscle activity, and the number of chewing cycles until swallowing. However, auditory, and/or visual masking significantly increased the chewing cycle duration (Van Der Bilt et al., 2011).

In contrast to solid foods, liquid and semi-solid foods require little more than transport of the food from the front of the mouth to the oropharynx (de Wijk et al., 2008). Variations in oral processing behavior may therefore primarily reflect variations in the food's hedonic and sensory properties (de Wijk et al., 2008). For example, de Wijk et al. (2008) quantified the oral activity during the processing of starch-based vanilla custards with five different levels of viscosity by using vibromyography (VMG) technology and compared these with sensory judgments. The authors found that thickness ratings were related primarily to the activity of the temporalis muscle, suggesting a relatively simple up and down movement of the tongue. Increased viscosity may result in increased muscle tension if the rate of tongue movement remains constant or decreased movement if the tension remains constant. The fact that higher thickness ratings were associated with lower muscle activity suggests that VMG reflects movement rather than tension. Similarly, Nakauma et al. (2011) investigated the relationship between swallowing profiles (via acoustic analysis) and sensory perceived scores using food polysaccharide solutions (xanthan gum and locust bean gum) with various viscosities (0.3-0.9%). The authors reported that the time required for the bolus to transfer through the pharyngeal phase (t2) decreased with increasing concentration of xanthan gum despite the viscosity increase. The t2 for locust bean gum was much less concentration-dependent and consistently larger than that for xanthan gum. Results of a study by Nakuama et al. (2011) indicated that even though some samples might have similar viscosity scores, as determined by sensory judgments, their swallowing profiles might be slightly different. Xanthan gum solutions flow as one coherent bolus through the pharyngeal phase with a smaller variation of flow velocity than locust bean gum solutions, leading to a greater sensation of swallowing ease. “Structured fluid”, defined as fluid with yield stress such as xanthan gum solutions, have a rheological nature that allows the bolus to be swallowed in one go, relating to perceived swallowing ease of liquid foods (Nakauma et al., 2011).

6. Effect of hearing loss on food perception and enjoyment

To date, no studies have investigated the effects of hearing loss on food perception. Jutras et al. (2019), in an effort to mimic conductive hearing loss, investigated the effect of external ear occlusion on sound pressure level while eating (recorded with a probe microphone placed in the external ear canal), as well as on food perception in adults with normal hearing. Participants in Jutras et al. (2019) rated the freshness and taste of five crispy and five soft food items with and without an earplug. Compared to the open ear canal condition, Jutras et al. (2019) found that levels of the mastication sounds were higher when the participants had their ears occluded, for crispy and soft food. Regarding food freshness, food appreciation, and willingness to eat more of the same food, there was no significant difference concerning food type, ear condition, and gender.

References

Abrams, H. B., Chisolm, T. H., & McArdle, R. (2005). Health-related quality of life and hearing aids: a tutorial. *Trends in Amplification, 9*(3), 99-109. https://doi.org/10.1177/108471380500900302

American Speech-Language-Hearing Association (ASHA). (2019). *Hearing loss: beyond early childhood*. Retrieved January 17 from https://www.asha.org/practice-portal/clinical-topics/hearing-loss/.

Bagai, A., Thavendiranathan, P., & Detsky, A. S. (2006). Does this patient have hearing impairment? *JAMA, 295*(4), 416-428. https://doi.org/10.1001/jama.295.4.416

Bat-Chava, Y., & Deignan, E. (2001). Peer relationships of children with cochlear implants. *The Journal of Deaf Studies and Deaf Education, 6*(3), 186-199. https://doi.org/10.1093/deafed/6.3.186

Belluz, J. (2018). *Why restaurants became so loud — and how to fight back. "I can't hear you."* Retrieved January 17 from https://www.vox.com/2018/4/18/17168504/restaurants-noise-levelsloud-decibels

Bracewell, R. N. (1978). *The Fourier transform and its applications* (2nd ed.). McGraw-Hill.

Bruns, A. J., & Bourne, M. C. (2007). Effects of sample dimensions on the snapping force of crisp foods. *Journal of Texture Studies, 6*(4), 445-458. https://doi.org/10.1111/j.1745-4603.1975.tb01420.x

Carlsson, P. I., Hjaldahl, J., Magnuson, A., Ternevall, E., Eden, M., Skagerstrand, A., & Jonsson, R. (2015). Severe to profound hearing impairment: quality of life, psychosocial consequences and audiological rehabilitation. *Disability and Rehabilitation, 37*(20), 1849-1856. https://doi.org/10.3109/09638288.2014.982833

Chakra, W., Allaf, K., & Jemai, A. B. (1996). Characterization of brittle food products: application of the acoustical emission method. *Journal of Texture Studies, 27*(3), 327-348. https://doi.org/10.1111/j.1745-4603.1996.tb00078.x

Chien, W., & Lin, F. R. (2012). Prevalence of hearing aid use among older adults in the United States. *Archives of Internal Medicine, 172*(3), 292-293. https://doi.org/10.1001/archinternmed.2011.1408

Christensen, C. M., & Vickers, Z. M. (1981). Relationships of chewing sounds to judgments of food crispness. *Journal of Food Science, 46*(2), 574-578. https://doi.org/10.1111/j.1365-2621.1981.tb04914.x

Chung, K. (2004). Challenges and recent developments in hearing aids. Part I. Speech understanding in noise, microphone technologies and noise reduction algorithms. *Trends in Amplification, 8*(3), 83-124. https://doi.org/10.1177/108471380400800302

Clark, J. G. (1981). Uses and abuses of hearing loss classification. *ASHA, 23*(7), 493-500. https://www.ncbi.nlm.nih.gov/pubmed/7052898

Dacremont, C. (1995). Spectral composition of eating sounds generated by crispy, crunchy and crackly foods. *Journal of Texture Studies, 26*(1), 27-43. https://doi.org/10.1111/j.1745-4603.1995.tb00782.x

Dacremont, C., Colas, B., & Sauvageot, F. (1991). Contribution of air-and bone-conduction to the creation of sounds perceived during sensory evaluation of foods. *Journal of Texture Studies, 22*(4), 443-456. https://doi.org/10.1111/j.1745-4603.1991.tb00503.x

Dalton, D. S., Cruickshanks, K. J., Klein, B. E., Klein, R., Wiley, T. L., & Nondahl, D. M. (2003). The impact of hearing loss on quality of life in older adults. *Gerontologist, 43*(5), 661-668. https://doi.org/10.1093/geront/43.5.661

Dawes, P., Emsley, R., Cruickshanks, K. J., Moore, D. R., Fortnum, H., Edmondson-Jones, M., McCormack, A., & Munro, K. J. (2015). Hearing loss and cognition: the role of hearing AIDS, social isolation and depression. *PloS One, 10*(3), e0119616. https://doi.org/10.1371/journal.pone.0119616

de Wijk, R. A., Polet, I. A., Bult, J. H., & Prinz, J. F. (2008). Vibromyography of oral processing varies with type of semi-solid food and with sensory judgements. *Physiology & Behavior, 95*(3), 521-526. https://doi.org/10.1016/j.physbeh.2008.07.028

Demattè, M. L., Pojer, N., Endrizzi, I., Corollaro, M. L., Betta, E., Aprea, E., Charles, M., Biasioli, F., Zampini, M., & Gasperi, F. (2014). Effects of the sound of the bite on apple perceived crispness and hardness. *Food Quality and Preference, 38*, 58-64. https://doi.org/10.1016/j.foodqual.2014.05.009

Drake, B. K. (1963). Food crushing sounds. An introductory study. *Journal of Food Science, 28*(2), 233-241. https://doi.org/10.1111/j.1365-2621.1963.tb00190.x

Duizer, L. M., Campanella, O. H., & Barnes, G. R. G. (1998). Sensory, instrumental and acoustic characteristics of extruded snack food products. *Journal of Texture Studies, 29*(4), 397-411. https://doi.org/10.1111/j.1745-4603.1998.tb00812.x

Edmister, J. A., & Vickers, Z. M. (1985). Instrumental acoustical measures of crispness in foods. *Journal of Texture Studies, 16*(2), 153-167. https://doi.org/10.1111/j.1745-4603.1985.tb00688.x

Eggermont, J. J. (2014). *Noise and the brain. Experience dependent developmental and adult plasticity*. (1st ed.). Academic Press.

Eggermont, J. J. (2017). *Hearing loss: causes, prevention, and treatment* (1st ed.). Academic Press.

Endo, H., Ino, S., & Fujisaki, W. (2016). The effect of a crunchy pseudo-chewing sound on perceived texture of softened foods. *Physiology & Behavior*, *167*, 324-331. https://doi.org/10.1016/j.physbeh.2016.10.001

Endo, H., Ino, S., & Fujisaki, W. (2017). Texture-dependent effects of pseudo-chewing sound on perceived food texture and evoked feelings in response to nursing care foods. *Appetite*, *116*, 493-501. https://doi.org/10.1016/j.appet.2017.05.051

González, R., Montoya, I., & Cárcel, J. (2016). Review: the use of electromyography on food texture assessment. *Food Science and Technology International*, *7*(6), 461-471. https://doi.org/10.1106/nrht-l39d-hy1y-8rgb

Gopinath, B., Schneider, J., Hickson, L., McMahon, C. M., Burlutsky, G., Leeder, S. R., & Mitchell, P. (2012). Hearing handicap, rather than measured hearing impairment, predicts poorer quality of life over 10 years in older adults. *Maturitas*, *72*(2), 146-151. https://doi.org/10.1016/j.maturitas.2012.03.010

Humes, L. E., Dubno, J. R., Gordon-Salant, S., Lister, J. J., Cacace, A. T., Cruickshanks, K. J., Gates, G. A., Wilson, R. H., & Wingfield, A. (2012). Central presbycusis: a review and evaluation of the evidence. *Journal of the American Academy of Audiology, 23*(8), 635-666. https://doi.org/10.3766/jaaa.23.8.5

Humes, L. E., Rogers, S. E., Quigley, T. M., Main, A. K., Kinney, D. L., & Herring, C. (2017). The effects of service-delivery model and purchase price on hearing-aid outcomes in older adults: a randomized double-blind placebo-controlled clinical trial. *American Journal of Audiology, 26*(1), 53-79. https://doi.org/10.1044/2017_AJA-16-0111

Jee, J., Wang, J. J., Rose, K. A., Lindley, R., Landau, P., & Mitchell, P. (2005). Vision and hearing impairment in aged care clients. *Ophthalmic Epidemiology, 12*(3), 199-205. https://doi.org/10.1080/09286580590969707

Jowitt, R. (1974). The terminology of food texture. *Journal of Texture Studies, 5*(3), 351-358. https://doi.org/10.1111/j.1745-4603.1974.tb01441.x

Jutras, B., Luond, A., Honegger, F., Stieger, C., Hummel, T., & Welge-Lussen, A. (2019). Influence of external ear occlusion on food perception. *European Archives of Oto-Rhino-Laryngology, 276*(3), 889-895. https://doi.org/10.1007/s00405-019-05296-w

Kaplan-Neeman, R., Muchnik, C., Hildesheimer, M., & Henkin, Y. (2012). Hearing aid satisfaction and use in the advanced digital era. *Laryngoscope*, *122*(9), 2029-2036. https://doi.org/10.1002/lary.23404

Kapur, K. K. (1971). Frequency spectrographic analysis of bone conducted chewing sounds in persons with natural and artificial dentitions. *Journal of Texture Studies, 2*(1), 50-61. https://doi.org/10.1111/j.1745-4603.1971.tb00272.x

Kidd, G., Jr., Mason, C. R., Best, V., & Swaminathan, J. (2015). Benefits of acoustic beamforming for solving the cocktail party problem. *Trends in Hearing, 19*. https://doi.org/10.1177/2331216515593385

Kinsler, L. E., & Frey, A. R. *Fundamentals of acoustics* (2nd ed.). John Wiley and Sons.

Kitterick, P. T., & Ferguson, M. A. (2018). Hearing aids and health-related quality of life in adults with hearing loss. *JAMA, 319*(21), 2225-2226. https://doi.org/10.1001/jama.2018.5567

Kohyama, K., Sasaki, T., & Hayakawa, F. (2008). Characterization of food physical properties by the mastication parameters measured by electromyography of the jaw-closing muscles and mandibular kinematics in young adults. *Bioscience Biotechnology and Biochemistry, 72*(7), 1690-1695. https://doi.org/10.1271/bbb.70769

Lebo, C. P., Smith, M. F., Mosher, E. R., Jelonek, S. J., Schwind, D. R., Decker, K. E., Krusemark, H. J., & Kurz, P. L. (1994). Restaurant noise, hearing loss, and hearing aids. *Western Journal of Medicine, 161*(1), 45-49. https://doi.org/PMCID: PMC1011367.

Mills, J. H., Adkins, W. Y., & Gilbert, R. M. (1981). Temporary threshold shifts produced by wideband noise. *Journal of the Acoustical Society of America, 70*(2), 390-396. https://doi.org/10.1121/1.386774

Moir, J. (2015). *Why are restaurants so noisy? Can't hear a word your other half says when you dine out? Our test proves restaurants can be a loud as rock concerts.* Retrieved January 17 from http://www.dailymail.co.uk/news/article-3346929/Why-restaurants-noisy-thear-word-half-says-dine-test-proves-restaurants-loud-rock-concerts.html.

Moore, B. C. J. (2013). *An introduction to the psychology of hearing* (6th ed.). Academic Press.

Mosher, E. R., & Jelonek, S. J. (1991). Real ear measurement of noise and aided performance in noise. In Proceedings of the American Speech, Hearing, and Language Association meeting, Atlanta, GA.

Mulrow, C. D., Aguilar, C., Endicott, J. E., Tuley, M. R., Velez, R., Charlip, W. S., Rhodes, M. C., Hill, J. A., & DeNino, L. A. (1990). Quality-of-life changes and hearing impairment. A randomized trial. *Annals of Internal Medicine, 113*(3), 188-194. https://doi.org/10.7326/0003-4819-113-3-188

Nakauma, M., Ishihara, S., Funami, T., & Nishinari, K. (2011). Swallowing profiles of food polysaccharide solutions with different flow behaviors. *Food Hydrocolloids, 25*(5), 1165-1173. https://doi.org/https://doi.org/10.1016/j.foodhyd.2010.11.003

National Institute for Occupational Safety and Health (NIOSH). (1996). *Preventing occupational hearing loss: A practical guide (Report No. 96-10)*. U.S department of Health and Human Services. Cincinnati, OH. www.asha.org/Practice-Portal/Professional-Issues/Adult-Hearing-Screening/.

Nelson, D. I., Nelson, R. Y., Concha-Barrientos, M., & Fingerhut, M. (2005). The global burden of occupational noise-induced hearing loss. *American Journal of Industrial Medicine, 48*(6), 446-458. https://doi.org/10.1002/ajim.20223

Nixon, C. W., Johnson, D. L., & Stephenson, M. R. (1977). Asymptotic behavior of temporary threshold shift and recovery from 24- and 48-hour noise exposures. *Aviation, Space, and Environmental Medicine, 48*(4), 311-315. https://doi.org/PMID: 871291

Norena, A. J., Gourevitch, B., Aizawa, N., & Eggermont, J. J. (2006). Spectrally enhanced acoustic environment disrupts frequency representation in cat auditory cortex. *Nature Neuroscience, 9*(7), 932-939. https://doi.org/10.1038/nn1720

Pellegrino, R., Jones, J. D., Shupe, G. E., & Luckett, C. R. (2019). Sensitivity to viscosity changes and subsequent estimates of satiety across different senses. *Appetite, 133*, 101-106. https://doi.org/10.1016/j.appet.2018.10.028

Purves, D., Augustine, G. J., Fitzpatrick, D., Hall, W. C., LaMantia, A.-S., McNamara, J. O., & Williams, S. M. (2004). *Neuroscience*. Sinauer.

Schuknecht, H. F. (1955). Presbycusis. *Laryngoscope, 65*(6), 402-419. https://doi.org/10.1288/00005537-195506000-00002

Sergeyenko, Y., Lall, K., Liberman, M. C., & Kujawa, S. G. (2013). Age-related cochlear synaptopathy: an early-onset contributor to auditory functional decline. *Journal of Neuroscience, 33*(34), 13686-13694. https://doi.org/10.1523/JNEUROSCI.1783-13.2013

Spence, C. (2014). Noise and its impact on the perception of food and drink. *Flavour, 3*(1). https://doi.org/10.1186/2044-7248-3-9

Spence, C., & Wang, Q. (2015). Sensory expectations elicited by the sounds of opening the packaging and pouring a beverage. *Flavour, 4*(1), 35. https://doi.org/10.1186/s13411-015-0044-y

Spence, C., & Zampini, M. (2006). Auditory contributions to multisensory product perception. *Acta Acustica united with Acustica, 92*(6), 1009-1025. https://doi.org/124275922

Szczesniak, A. S. (1988). The meaning of textural characteristics - crispness. *Journal of Texture Studies, 19*(1), 51-59. https://doi.org/10.1111/j.1745-4603.1988.tb00924.x

Valente, M., & Mispagel, K. M. (2008). Unaided and aided performance with a directional open-fit hearing aid. *International Journal of Audiology, 47*(6), 329-336. https://doi.org/10.1080/14992020801894832

van der Bilt, A., Pocztaruk, R. L., Frasca, L. C., van der Glas, H. W., & Abbink, J. H. (2011). The influence of auditory and visual information on the neuromuscular control of chewing crispy food. *European Journal of Oral Sciences, 119*(6), 427-434. https://doi.org/10.1111/j.1600-0722.2011.00878.x

Velasco, C., Jones, R., King, S., & Spence, C. (2013). The sound of temperature: what information do pouring sounds convey concerning the temperature of a beverage. *Journal of Sensory Studies, 28*(5), 335-345. https://doi.org/10.1111/joss.12052

Viana, L. M., O'Malley, J. T., Burgess, B. J., Jones, D. D., Oliveira, C. A., Santos, F., Merchant, S. N., Liberman, L. D., & Liberman, M. C. (2015). Cochlear neuropathy in human presbycusis: Confocal analysis of hidden hearing loss in post-mortem tissue. *Hearing Research, 327*, 78-88. https://doi.org/10.1016/j.heares.2015.04.014

Vickers, Z. (1991). Sound perception and food quality. *Journal of Food Quality, 14*(1), 87-96. https://doi.org/10.1111/j.1745-4557.1991.tb00049.x

Vickers, Z., & Bourne, M. C. (1976). A psychoacoustical theory of crispness. *Journal of Food Science, 41*(5), 1158-1164. https://doi.org/10.1111/j.1365-2621.1976.tb14407.x

Vickers, Z. M. (1982). Relationships of chewing sounds to judgments of crispness, crunchiness and hardness. *Journal of Food Science, 47*(1), 121-124. https://doi.org/10.1111/j.1365-2621.1982.tb11041.x

Wang, Q. J., & Spence, C. (2015). Assessing the effect of musical congruency on wine tasting in a live performance setting. *Iperception, 6*(3), 2041669515593027. https://doi.org/10.1177/2041669515593027

Wang, Q. J., & Spence, C. (2019). Sonic packaging: how packaging sounds influence multisensory product evaluation. In C. Velasco & C. Spence (Eds.), *Multisensory Packaging* (pp. 103-125). Springer International Publishing. https://doi.org/10.1007/978-3-319-94977-2_5

Wie, O. B. (2010). Language development in children after receiving bilateral cochlear implants between 5 and 18 months. *International Journal of Pediatric Otorhinolaryngology, 74*(11), 1258-1266. https://doi.org/10.1016/j.ijporl.2010.07.026

Woods, A. T., Poliakoff, E., Lloyd, D. M., Kuenzel, J., Hodson, R., Gonda, H., Batchelor, J., Dijksterhuis, G. B., & Thomas, A. (2011). Effect of background noise on food perception. *Food Quality and Preference, 22*(1), 42-47. https://doi.org/10.1016/j.foodqual.2010.07.003

Zampini, M., & Spence, C. (2004). The role of auditory cues in modulating the perceived crispness and staleness of potato chips. *Journal of Sensory Studies*, *19*(5), 347-363. https://doi.org/10.1111/j.1745-459x.2004.080403.x

Zampini, M., & Spence, C. (2005). Modifying the multisensory perception of a carbonated beverage using auditory cues. *Food Quality and Preference*, *16*(7), 632-641. https://doi.org/10.1016/j.foodqual.2004.11.004

Chapter 3 - Impacts of hearing loss on sensory perception and acceptance of food samples varying in crispness or viscosity

Abstract

The impact of hearing loss is profound, with consequences for the functional, and psychological well-being of the person. Surprisingly, very little attention has been paid to whether auditory loss can significantly impact consumers' sensory perception and overall enjoyment of food. This research aimed to determine the impacts of hearing loss on the sensory perception and acceptance of solid or liquid food samples. More specifically, solid food samples with varying levels of crispness, and liquid food samples with various levels of viscosity were evaluated by individuals with hearing loss (HL) and individuals with normal hearing (NH). HL and NH groups were asked to evaluate the crispness, loudness, pitch, and acceptance of solid foods and the viscosity, loudness, and acceptance of liquid foods. Results showed that hearing loss impacted the overall acceptance and loudness perception of solid food samples. Pitch intensity was found as a significant negative contributor to the overall liking of solid food samples in the HL group. In addition, the HL group was not able to discriminate solid food samples with a smaller difference in crispness. Loudness perception of liquid foods was also impacted by hearing loss. HL rated liquid samples as less loud compared to NH individuals. No impact of hearing loss was observed on the overall enjoyment of liquid samples. In conclusion, this study showed the impacts of hearing loss on the perception and enjoyment of solid and liquid foods with an intrinsic sound component. The results of this study encourage sensory professionals to offer new strategies for the improvement of dietary choices and enjoyment of food for consumers with auditory loss.

Keywords: hearing loss, texture, crispness, viscosity, sensory perception, food acceptance.

1. Introduction

The sense of hearing is perhaps one of the most overlooked senses by consumers when thinking about the overall eating experience. Smell, sight, and taste are commonly listed first in order of importance by consumers (Laureati et al., 2006; Schifferstein, 2006), and hearing often seems to play a secondary, contextually less conscious role (Laureati et al., 2006). However, it has been established that the perception of food and beverages is modulated by all senses, and everyday food-related experiences are more of a multisensory interaction and integration than previously assumed. In other words, food perception is not isolated to one individual sense but rather is the result of a non-linear integration of all the single sensory modalities (Calvert et al., 2004; Spence & Shankar, 2010). Auditory cues have shown to play a major role in the various phases of interaction between consumers and food products, from the moment food packaging is opened (Brown, 1958; Velasco et al., 2016; Knöferle, 2012; Spence & Wang, 2015) to the amount of food or beverage consumed (Bach & Schaefer 1979; Jacob, 2006; Guéguen et al., 2008). Additionally, the sounds elicited by the food during eating (product-intrinsic sounds) have shown to modulate consumers taste (Spence et al., 2011; Crisinel & Spence; 2009), flavor (Bronner et al., 2008; Spence et al., 2011, Luckett et al., 2016), and texture perception (Zampini & Spence, 2004; Demattè et al., 2014; Varela et al., 2007) of food.

Texture perception and the sounds emitted by solid, and liquid foods during eating have shown an exceptionally tight interrelationship. Vickers (1982) found that perceived crispness and loudness of chewing sounds were highly correlated in the mind of the consumers after subjects separately judged the sounds and the crispness of a wide range of wet and dry crisp foods in a similar manner (Vickers, 1982). The effect of sound on the perception of crispiness, crunchiness, and crackliness attributes has been frequently explored in solid food matrices. For example, Zampini and Spence (2004) demonstrated that the perception of the crispness and freshness of potato chips was affected by varying the loudness and/or frequency composition of the auditory feedback elicited during the biting action. The potato chips were perceived as being both crisper and fresher when either the overall sound level was increased, or when the high-frequency sounds (in the range of 2 kHz−20 kHz) were selectively amplified (Zampini & Spence, 2004). Similarly, Demattè et al. (2014) found that the perceived crispness of apples was rated significantly lower when high-frequency sounds (by −12 dB or by −24 dB) were presented via headphones during the biting action as compared to when no filter (0 dB) was used. To a lesser extent than solid foods, the perception of textural or mouthfeel attributes of liquid food has also shown to be modulated by the sounds emitted by the food. Pellegrino et al. (2019) designed a study to compare and contrast the sensitivity of humans to changes in viscosity through different sensory modalities (visual, auditory, and oral tactile). Pellegrino et al. (2019) discovered that oral tactile and audition proved to be the most sensitive modalities to changes in viscosity as compared to the visual modality (Pellegrino et al., 2019). Similarly, Spence and Wang (2015) found that consumers can discriminate among the pouring sounds of various sucrose solutions with different concentrations (0, 25, and 50% w/w) and viscosities (Spence & Wang, 2015). It is important to highlight that the previously mentioned studies looking into the effects of sound on viscosity perception focused on the effects of pouring sounds (auditory approach) and did not look into the potential of oral sensations (oral approach).

Although, as of 2019, hearing loss is a sensory disorder affecting more than 1.57 billion people worldwide (Haile et al., 2021)little effort has been made to determine how a hearing loss may impact an individual's texture perception and acceptance of food. Jutras et al. (2019) attempted to mimic the effects of conductive hearing loss on the perception of crispness, freshness, and hedonic values of various crispy and non-crispy food products by occluding the external ear canal of subjects with normal hearing. The later-mentioned study found that plugging the ear canal increased mastication sound levels (measured via a probe microphone placed in the external ear canal) but did not have an effect on food freshness, food appreciation, and willingness to eat the specific food (Jutras et al., 2019). However, as previously emphasized, Jutras et al. (2019) employed individuals with normal hearing for their study rather than individuals with hearing loss, leaving some unanswered questions about this segment of the population. For example, even though an occlusion of the ear canal may be a fair representation of what occurs during conductive hearing loss, there are alterations at the brain and at the neuronal level implicated in some types of hearing loss (i.e., sensorineural hearing loss) that need to be considered. Sensorineural hearing loss occurs when there is damage to the inner ear (cochlea) or the nerve pathways from the inner ear to the brain (Eggermont, 2013). Thus, the question remains. What would occur to our overall perception of food and food enjoyment when the sense of hearing fails? Sensory deficiencies have shown to negatively impact the eating and food-related difficulties that come along with the sensory loss. For example, 69% of patients with olfactory loss reported a decrease in food enjoyment after the onset of the disorder (Ferris & Duffy, 1989). The present study was designed to evaluate the impact of hearing loss on texture perception and acceptance of food. More specifically, solid food samples with varying levels of crispness, and liquid food matrices with various levels of viscosity.

2. Materials and Methods

This study was conducted in conformance with the Declaration of Helsinki for studies on human subjects. The protocol used in this was approved by the Institutional Review Board of the University of Arkansas (Fayetteville, AR, USA). Written informed consent was obtained from each participant before participation.

2.1 Participants

Table 1 shows the participants demographic profiles. A total of 37 individuals with hearing loss (HL) (based on self-report diagnoses) [18 females and 19 males; mean age ± standard deviation (SD) = 59 ± 13 years old], and 37 individuals with normal hearing (NH) [17 females and 20 males; mean age ± standard deviation (SD) = 61 ± 13 years old] were recruited via the consumer profile database of the University of Arkansas Sensory Science Center, hearing clinics, deaf clubs, and the University of Arkansas campus. Both HL and NH groups did not significantly differ in terms of mean age (P = 0.35) or gender ratio (P = 1.00). All of the HL participants were diagnosed with a bilateral hearing loss. Approximately 45% of HL participants that participated in this study had been diagnosed with sensorineural hearing loss, 48.6% of HL individuals had a moderately severe (56 to 70 dB HL) or higher degree of hearing loss and 54% of them indicated having a high-frequency hearing loss configuration. In addition, approximately 48% indicated wearing a hearing assistive device such as hearing aids. Volunteers that reported having dentures, food allergies or cognitive impairments were not included in the study. All NH individuals showed evidence of normal auditory status. Auditory acuity of NH individuals was assessed via the adult hearing screening procedure recommended by the American Speech-Language-Hearing Association (ASHA) (ASHA, 2022). The hearing screening consisted of three components: a brief case history (e.g., review of chronic diseases, medications, and family history), a visual otoscopic inspection employing an otoscope with throat illuminator (Model 22821, Welch Allyn, Inc., Skaneateles Falls, New York, USA), and the use of calibrated pure-tone signals (ASHA, 2022). Pure-tone signals were routed via circumaural earphones with a portable audiometer (Earscan 3; Micro Audiometrics Corp, Murphy, NC, USA). A pass result was documented if no concerns were reported during the case history, no abnormal findings were observed during the otoscopy examination, and responses were obtained in both ears to pure-tone air-conduction stimuli at 25 dB HL at 1000 Hz, 2000 Hz, and 4000 Hz (ASHA, 2022).

2.2 Food samples

Table 2 shows the solid and liquid food samples selected for this study. These samples were selected based on the Spectrum scale for crispness and viscosity (Meilgaard et al., 2015). The Spectrum scale of intensity is a validated descriptive analysis tool that employs a standardized universal scale ranging from 0 = none to 15 = very strong (Meilgaard et al., 2015). The samples were chosen in order to represent low and high intensities, as well as small and large texture differences within each food matrix. All samples were available commercially and were purchased from the local supermarket in Fayetteville, AR, USA.

2.3 Procedure

Prior to sample presentation, participants were shown written instructions about the experimental procedure. The evaluations were done in a quiet room to avoid the influence of external sounds on sample evaluation. HL individuals were instructed to remove their hearing aids if they were wearing any. All participants experienced two experimental sessions in a randomized order. During one of the sessions, participants were presented with solid food samples, and during the other session participants were presented with liquid food samples. The sessions were counterbalanced across participants to eliminate any order effects and were conducted on two separate days with one-week apart. To determine if participants were able to discriminate between small or large differences on crispness and viscosity, samples on each session were presented to the participants in two stages separated by a three-minute break. The first stage focused on samples with smaller texture differences and the second stage on samples with larger texture differences.

More specifically, during the solid food session the club crackers (crispness intensity = 5.0) and the oat cereal (7.0) were presented in a monadic sequential way during the first stage, since these two samples only have a two-point of intensity difference in the Spectrum crispness scale. During the second stage the granola bar (crispness intensity = 2.0), oat cereal (7.0), and melba toast (17.0) were presented one after the other, representing the samples with larger differences in crispness. Similarly, for the liquid food session, samples with smaller differences in viscosity such as heavy cream (viscosity intensity = 4.0) and maple syrup (6.0) were presented to participants during the first stage, and samples with larger viscosity differences such as half & half cream (viscosity intensity = 2.0), chocolate syrup (9.0), and sweetened condensed milk (14.5) were presented during the second stage. Food samples within each stage were randomized using a Williams Latin square design (Williams, 1949). Between sample presentations, a brief break was given for 60 s with unsalted crackers (Nabisco Premium, Mondelēz Intl., East Hanover, NJ, USA) and spring water (Clear Mountain Spring Water, Taylor Distributing, Heber Springs, AR, USA) for palate cleansing.

For the solid samples participants were asked to rate the samples in terms of their perceived crispness, loudness, and pitch-intensity on a 100-mm line scale ranging from 0 (not at all) to 100 (extremely intense). Perceived crispness, loudness, and pitch intensities of test samples were also measured on Just-About-Right (JAR) scales (1 = much too little, 4 = JAR, and 7 = much too much), respectively. For the liquid samples, participants were asked to rate the samples in terms of their perceived intensities of viscosity and loudness during swallowing intensity on a 100-mm line scale ranging from 0 (not at all) to 100 (extremely intense), respectively. Perceived intensities of viscosity and loudness were also measured on JAR scales (1 = much too little, 4 = JAR, and 7 = much too much), respectively. Overall liking of solid or liquid samples were measured on9-point hedonic scales ranging from 1 (dislike extremely) to 9 (like extremely). Following sensory evaluation and at the end of each stage (smaller or larger differences stage) participants were presented with the samples once again and asked to rank the samples from least to most crispy (or viscous), for solid (or liquid) samples.

Participants' facial expressions (FEs) were recorded with a Logitech C920 HD Pro webcam on iMotions platform (version 8.0, iMotions, Inc., MA, USA) before (referred as pre-consumption) and after consumption of the samples (referred as post-consumption). Recordings from participants were saved as MP4 files and analyzed frame by frame via FaceReader software version 8.0 (Noldus Information Technology, Wageningen, The Netherlands) according to the procedures suggested in previous studies (Gunaratne et al., 2019; Danner et al. 2014, Kaneko et al., 2019; and de Wijk et al., 2014). An event mark was placed on each video recording from the moment the hand holding the sample fell below the chin to 5 s post-consumption (Leitch et al., 2015; de Wijk et al., 2014; Samant et al., 2017). FaceReader extracted 7 basic emotions (happy, sad, angry, surprised, scared, disgusted and contempt), two emotional dimensions (valence and arousal), neutral states from the videos. Emotions were expressed as a value from 0 to 1 in each frame, indicating the intensity of the emotion. "0" means that the emotion is not visible in the facial expression, "1" means that the emotion is fully present. Calibration procedures were conducted for each participant to correct for person-specific biases toward a certain FE by subtracting the responses obtained during the "pre-consumption" stage from those obtained during the "post-consumption" stage of each sample, for all participants (Samant et al., 2017). These values were used for further statistical analysis. Mean values were obtained as intensities for each emotion.

2.4 Statistical Analysis

Statistical analyses were performed using JMP® Pro (version 16.0, SAS Institute Inc., Cary, NS, USA) and XLSTAT software (Addinsoft, New York, NY, USA). To determine the impacts of hearing loss on the discrimination ability of smaller or larger differences in either crispness or viscosity attribute, a two-way mixed model was performed treating "food samples" as a fixed effect and "panelist" as a random effect, for each hearing group (Worch et al., 2010). Friedman's test was employed to analyze the ranking data obtained for samples with smaller differences or larger differences in R 3.5.1 with the SensR sensory package version 1.5-2 (Brockhoff & Linander, 2017). If a significant difference was detected by the Friedman's test, multiple comparisons between the independent variables were conducted using Conover's procedure.

To determine the effect of hearing acuity on sensory perceptions, hedonic ratings, and facial expressions emotions for all stages combined a three-way mixed model, treating "hearing group" and "food samples" as fixed effects and "panelist" as a random effect, was employed. For the solid food samples since the sample "oat cereal' was evaluated twice by the participants (small and large difference stages) only the first score was employed for analysis. If a significant effect was identified, *post hoc* multiple pairwise comparisons between independent variables were conducted using Student *t*- tests. For each hearing group, stepwise multivariate regression analysis was performed to investigate the contribution of ratings of each sensory attribute on the overall acceptability of the samples. To determine associations between JAR data and hearing groups, a correspondence analysis (CA) was conducted. For the CA analysis, the JAR scale was considered nominal, and the original data was recoded in three points, combining 1, 2, and 3 as "not enough", 4 as "JAR", and 5, 6 and 7 as "too much". The level of similarity between the two hearing groups CA configurations was measured using a regression vector (RV) coefficient considered to be a correlation coefficient in a multidimensional configuration (Chapko & Seo, 2019; Schlich, 1996). For all analyses, a statistically significant difference was defined as $P < 0.05$.

3. Results

3.1 Solid foods

3.1.1 Effects of hearing loss on the discrimination of solid food samples with small or large differences in crispness

Figure 4 shows the results of two-way mixed model for solid samples with smaller differences in crispness as perceived by the HL and NH groups. For solid food samples with smaller differences in crispness, the NH group discriminated the samples with respect to “crispness” [$F(1, 36) = 6.7$, $P = 0.01$] and “loudness” [$F(1, 36) = 4.1$, $P = 0.05$]. Specifically, the NH group rated the club cracker sample as less crispy and less loud compared to the oat cereal. However, samples with smaller differences in crispness were not discriminated by the NH group in terms of “pitch” ($P = 0.19$). In the case of the HL group, samples were discriminated in terms of “loudness” [$F(1, 36) = 4.8$, $P = 0.03$], but not in terms of “crispness” ($P = 0.83$) and “pitch” ($P = 0.28$). As shown in Figure 5, for solid food samples with larger differences in crispness, “crispness” [$F(2, 72) = 117.9$, $P < 0.001$], “loudness” [$F(2, 72) = 65.0$, $P < 0.001$], and “pitch” [$F(2, 72) = 48.5$, $P < 0.001$] were discriminant attributes for the NH group. Similarly, the HL group was able to discriminate solid food samples with larger differences in crispness in terms of “crispness” [$F(2, 72) = 95.1$, $P < 0.001$], “loudness” [$F(2, 72) = 84.1$, $P < 0.001$], and “pitch” [$F(2, 72) = 26.5$, $P < 0.001$]. Both groups rated melba toast as the sample with higher crispness, loudness, and pitch, followed by the oat cereal and granola bar samples.

As shown in Table 4, Friedmans signed-rank test carried out on the crispness ranking data for samples with smaller differences or larger differences revealed that the NH group found the oat cereal significantly crispier than the club cracker [$\chi2(1) = 6.08$, $P = 0.01$]. However, the HL group was not able to discriminate between these two samples in terms of crispness ($P = 0.07$). For the ranking data of samples with larger differences in crispness both NH [$\chi2(2) = 72.05$, $P < 0.001$] and HL [$\chi2(2) = -57.14$, $P < 0.001$] groups were able to discriminate the samples significantly and accurately in terms of crispness (granola bar < oat cereal < melba toast).

3.1.2 Effects of hearing loss on sensory perception or hedonic impression of solid food samples with various crispness intensities

Table 3 shows mean ratings of each solid food sample evaluated by either NH or HL groups with respect to sensory perception or hedonic impression. A three-way mixed model revealed no significant interactions between "hearing group" and "food sample" on ratings of crispness intensity ($P = 0.44$), loudness intensity ($P = 0.40$), pitch intensity ($P = 0.46$), except for overall liking [$F(3, 216) = 3.04$, $P = 0.03$] (Table 3). *Post hoc t*-tests conducted to determine the source of interaction between hearing group and food samples on the overall liking ratings revealed that the HL group liked the melba toast sample significantly less compared to the NH group [$t(72) = -2.05$, $P = 0.04$]. No significant differences were found between the NH and HL groups on the overall liking scores of granola bar ($P = 0.55$), club cracker ($P = 0.40$) or oat cereal ($P = 0.13$).

The three-way mixed model revealed a significant main effect of "hearing group" on loudness ratings [$F(1, 72) = 5.83$, $P = 0.02$] (Table 3). HL group rated the samples to be significantly less loud compared to the NH group. No significant main effect of "hearing group" was found on intensity ratings of crispness ($P = 0.25$) or pitch ($P = 0.21$), and hedonic ratings ($P = 0.38$) (Table 3). In addition, "food sample" main effects were found on the crispness [$F(3, 216) = 157.44$, $P < 0.001$], and pitch scores [$F(3, 216) = 51.75$, $P < 0.001$]. *Post-hoc t*-test analyses showed that when both hearing groups are considered, participants rated the melba toast significantly crispier than the oat cereal, club cracker and granola bar samples. In addition, the granola bar sample was rated as the least crispy sample, but no significant differences were observed between the oat cereal and club cracker in terms of crispness scores. Similar results were observed with respect to pitch responses, where melba toast was considered significantly higher in pitch intensity compared to the oat cereal, club cracker and granola bar samples. The granola bar was also rated as the samples with lower intensity in pitch, but no significant differences were observed between the oat cereal and club cracker in terms of pitch scores. A significant main effect of "food sample" was also found on the loudness ratings [$F(3, 216) = 110.22$, $P < 0.001$]. *Post-hoc t*-test analyses found that when considering both hearing groups the melba toast sample was considered the louder sample, followed by the oat cereal, club cracker and the granola bar.

A stepwise regression did not find any of the sensory attributes (i.e., crispness, loudness, and pitch intensity) as significant predictors of the overall liking for the NH group ($P > 0.05$, for all). For the HL group, a regression model [$F(1, 147) = 25.95$, $P < 0.001$] using pitch intensity ($\beta = -0.04$) as a unique predictor was found to be the optimum model since it produced the highest R^2 (0.15), the lowest Root Mean Square Error (RMSE) (1.96), and lower values in Akaike Information Criterion (AIC) (622.78) and Bayesian Information Criterion (BIC) (631.60). Mallows' Cp for this model was 2.33.

Figure 1 (A-B) shows the biplots of the correspondence analysis (CA) on the JAR data, evaluated by the two hearing groups. The bi-plots of CA for the NH (Figure 1A) and HL (Figure 1B) groups accounted for 99.7% and 99.05% of the total variance, respectively. While the solid food samples show some differences with respect to JAR scores, the bi-plots exhibited minimal differences between the two hearing groups. An RV coefficient for measuring the degree of similarity between the two CA configurations obtained across the two hearing groups was 0.98 (*P*

< 0.001) suggesting a high similarity between the two hearing groups with respect to the discrimination pattern of solid food samples based on JAR scores.

3.1.3 Effects of hearing loss on FE emotional responses to solid food samples

A three-way mixed model revealed a significant interaction between "hearing group" and "food sample" on the intensity of "angry" FE responses [$F(3, 201) = 4.09$, $P = 0.008$] (Figure 2). *Post hoc t*-tests revealed that the melba toast sample elicited significantly more intense reactions of FE "angry" for the HL group compared to the NH group [$t(67) = 2.03$, $P = 0.04$]. But no significant differences were observed between the two hearing groups for the granola bar (P = 0.84), club cracker ($P = 0.16$) and oat cereal ($P = 0.67$) samples with respect to FE "angry" emotions. In addition, the three-way mixed model revealed a significant main effect of "hearing group" on the arousal responses [$F(1, 67) = 6.27$, $P = 0.01$] (Figure 3). The HL group showed lower intensities of FE "arousal" compared to the NH group. No significant interactions were found between "hearing group" and "food sample with respect to FE- based emotions ($P > 0.05$, for all). A significant main effect of "food sample" was found for the FE-based emotion arousal [$F(3, 201) = 2.68$, $P = 0.05$]. Supplementary Table 1 shows a full list of FE-based emotions for the solid samples evaluated by the NH and HL groups.

3.2. Liquid foods

3.2.1 Effects of hearing loss on the discrimination of liquid food samples with small or large differences in viscosity

Figure 7 shows the results of two-way mixed model for liquid samples with smaller or larger differences in viscosity as perceived by the NH and HL groups. For liquid food samples with smaller differences in viscosity, NH discriminated the samples with respect to "viscosity" [$F(1, 36) = 45.50$, $P < 0.001$] and "loudness" [$F(1, 36) = 13.56$, $P = 0.001$]. For the HL group, samples with smaller differences in viscosity were discriminated in terms of “viscosity” [$F(1, 36) = 26.83$, $P < 0.001$], but not in terms of “loudness” ($P = 0.91$). Both groups rated the sample maple syrup as higher in viscosity than the heavy cream sample. The NH group also rated the maple syrup as louder compared to the heavy cream. As shown in Figure 8, for liquid food samples with larger differences in viscosity, “viscosity” [$F(2, 72) = 117.9$, $P < 0.001$], and “loudness” [$F(2, 72) = 48.5$, $P < 0.001$] were discriminant attributes for the NH group. In terms of viscosity, NH group rated the half-and-half sample as significantly less viscous than chocolate syrup and condensed milk. In addition, chocolate syrup was rated as significantly less viscous than condensed milk. With respect to loudness, NH group rated half and half as significantly less loud than condensed milk. However, chocolate syrup did not differ in terms of loudness from half-and-half and condensed milk for the NH group.

The HL group was able to discriminate liquid food samples with larger differences in viscosity in terms of “viscosity” [$F(2, 72) = 95.1$, $P < 0.001$], but not in terms of “loudness” ($P = 0.06$). While the HL group found the half-and-half sample less viscous compared to the chocolate syrup and condensed milk, this group did not discriminate viscosity differences between chocolate syrup and condensed milk.

Table 6 shows the rank sums of the viscosity ranking data for samples with smaller differences or larger differences. Friedman's test for samples with smaller differences in viscosity revealed that NH group found the maple syrup significantly more viscous than the heavy cream [$\chi2(1) = 22.73$, $P < 0.001$]. Similarly, the HL group ranked maple syrup significantly more viscous than heavy cream [$\chi2(1) = 22.73$, $P < 0.001$]. For the ranking data of samples with larger differences in viscosity both NH [$\chi2(2) = 63.14$, $P < 0.001$] and HL [$\chi2(2) = 70.22$, $P < 0.001$]

groups were able to discriminate the samples significantly and accurately in terms of viscosity (half and half < chocolate syrup < condensed milk) (Table 6).

3.2.2 Effects of hearing loss on sensory perception or hedonic impression of liquid food samples with various levels of viscosity

Mean ratings of each liquid food sample evaluated by either NH or HL groups with respect to sensory perception and hedonic impression are shown in Table 5. A three-way mixed model revealed no significant interactions between "hearing group" and "food sample" on ratings of viscosity intensity ($P = 0.50$), or overall liking ($P = 0.22$). A significant interaction between "food sample" and "hearing group" was found in terms of loudness intensity [$F(4, 288) = 2.46$, $P = 0.05$] (Table 5). *Post hoc t*-tests conducted to determine the source of interaction between hearing group and food samples on the loudness ratings revealed that the HL group rated the samples maple syrup [$t(72) = -2.16$, $P = 0.03$], chocolate syrup [$t(72) = -2.36$, $P = 0.02$], and condensed milk [$t(72) = -1.99$, $P = 0.05$] as significantly less loud compared to the NH group. The half-and-half and heavy cream samples were also rated as less loud by HL group; however, these did not reach statistical significance ($P = 0.59$ and $P= 0.55$, respectively). Furthermore, no significant main effects of "hearing group" were found on ratings of viscosity intensity ($P = 0.58$), and overall liking ($P = 0.38$) (Table 5). A significant main effect of "food sample" was found on the viscosity intensity [$F(4, 288) = 144.39$, $P < 0.001$], and overall liking scores [$F(4, 288) = 8.39$, $P < 0.001$]. When considering both hearing groups, condensed milk was rated as the sample with the highest viscosity, followed by chocolate syrup, maple syrup, heavy cream and half and half. However, no significant differences in viscosity were observed between the viscosity scores of chocolate syrup and maple syrup. In terms of overall, liking *post-hoc t*-tests showed that the samples were separated in two groups with respect to liking. More specifically, half and half and chocolate syrup were liked the most, and significantly differ from heavy cream, condensed milk and maple syrup that were liked the least.

For the HL group, a stepwise regression analysis found that a regression model using viscosity as a unique predictor (β = -0.02) was found to be the optimum model [$F(1, 183) = 6.53$, $P = 0.01$] since it produced the highest R^2 (0.03), the lowest RMSE (2.24) and lower values in AIC (828.88) and BIC (838.41). Cp for this model was 2.60. Similarly, for the NH group, a regression model using viscosity as a unique predictor (β = -0.03) was found to be the optimum model [$F(1, 183) = 26.43$, $P < 0.001$] with R^2 (0.12), the lowest RMSE (2.25), and lower values in AIC (828.69) and BIC (838.21). Cp for this model was 3.47.

Figure 6 (A-B) shows the biplots of the correspondence analysis (CA) on the JAR data, evaluated by the two hearing groups. The bi-plots of CA for the NH (Figure 6A) and HL (Figure 6B) groups accounted for 99.4% and 98.0% of the total variance, respectively. By visually exploring the CA configurations it is noted that the five liquid food samples differed with respect to JAR scores. However, each liquid food sample placed on the bi-plot exhibited minimal differences between the two hearing groups. These results were also supported by comparing the two bi-plots of CAs via RV coefficients. An RV coefficient for measuring the degree of similarity between the two CA configurations obtained across the two hearing groups was 0.97 ($P < 0.001$) suggested a high similarity between the two hearing groups with respect to the discrimination pattern of liquid food samples based on JAR scores.

3.2.3 Effects of hearing loss on FE emotional responses to liquid food samples

A three-way mixed model revealed no significant interactions between "hearing group" and "food sample" with respect to FE- based emotions ($P > 0.05$, for all). In addition, no significant main effects of "hearing group" were found for any of the FE-based emotions measured ($P >$

0.05, for all). A significant main effect of "food sample" was found for the FE-based emotions neutral [$F(4, 280) = 7.75$, $P < 0.001$], happy [$F(4, 280) = 4.41$, $P = 0.002$], surprised [$F(4, 280) = 4.47$, $P = 0.002$] and arousal [$F(4, 280) = 2.58$, $P = 0.04$]. Supplementary Table 2 shows a full list of FE-based emotions for the liquid samples evaluated by the NH and HL groups.

4. Discussion

Despite the relatively large body of evidence indicating that the sense of hearing is of great significance in the contribution of texture perception, not much focus has been paid to the impact that hearing loss could have on food perception. This study aimed to explore the differences in sensory perception and acceptance of food samples between individuals with normal hearing and with hearing loss. We hypothesized that due to the multimodal nature of food, hearing loss would significantly impact the way sensory attributes were perceived and further impact overall liking. Specifically, sensory properties with intrinsic sound qualities such as the loudness, pitch and crispness of solid foods, and the swallowing loudness and viscosity of liquid food samples would be negatively impacted by hearing loss.

4.1 Hearing loss impacted loudness perception, crispness discrimination, acceptance, and emotions of solid food samples.

The results from this study confirmed differences in loudness perception of solid food samples, between individuals with normal hearing and with hearing loss. In agreement with our hypothesis, individuals with hearing loss perceived the solid samples to be less loud than individuals with normal hearing. This comes as no surprise since it has been previously established that foodstuffs contain largely auditory sensations. Drake (1963) found that the loudness of crushing sounds differed between crispy and less-crispy products, with crispy foods producing louder sounds than non-crispy ones. Similarly, Kapur (1971) found that the sounds produced during the chewing of a crisp wafer were 2.2 times (or more) greater than those produced during the chewing of a soggy wafer. During eating, sounds produced by food are often conveyed to the inner ear by two paths: (1) through the air, outside the body (air-conduction) and (2) through the skull bones (bone conduction). Christensen and Vickers (1981), in order to determine the role of airborne and bone-conducted sounds in loudness judgments, asked consumers to evaluate various food samples by different mastication procedures (i.e., by biting food with incisors and by biting with incisors and then chewing). In their study, Christensen and Vickers demonstrated that for solid food samples, the perception of loudness is conveyed in the initial fracture of the food by the incisors (air-conducted sounds), and often the sensory cues produced by subsequent chewing (bone-conducted sounds) are ignored (Christensen & Vickers, 1981; Sherman & Deghaidy, 1978). Our participant group contains a mixture of individuals with sensorineural, conductive, and mixed (sensorineural and conductive) hearing loss. In the presence of sensorineural hearing loss, the perception of both air conduction and bone conduction is impaired, but, in the presence of conductive hearing loss, air conduction is compromised but bone conduction is unharmed (Isaacson & Vora, 2003; Michels et al., 2019; Tanna et al., 2022). Even though, the unequal sample sizes would not allow for statistical comparison between the three types of hearing loss, all of the individuals with hearing loss that participated in this study had an impaired ability to perceive air-conducted sounds, explaining the reduced perception of loudness of the solid food samples.

A reduction in the perception of crispness was observed in the group with hearing loss as well. Specifically, a negative effect of hearing loss in the accurate discrimination of solid samples with smaller differences in crispness was found (Figure 4). Crispness is perceived through a combination of auditory, tactile, kinaesthetic, and visual sensations (Duizer 2001; Zampini & Spence 2004). Thus, the lack of auditory feedback that comes with hearing loss, as well as the decrease that was observed in perceived loudness may have impacted the crispness intensity to which solids samples were perceived, especially the samples with smaller crispness differences. The relationship between loudness and crispness has been widely documented by various researchers. Vickers (1985) asked volunteers to judge the crispness of a variety of food products by playing pre-recorded bite sounds and chewing sounds of the same. Vickers found that as the pitch and loudness increased, the perception of crispness increased, confirming her earlier study in which the panelists bit and chewed the food themselves (Vickers, 1984). Although the impact of auditory cues on the perception of crispness is well established, some authors have indicated that the evaluation of crispness is possible without the contribution of air-conducted noise (Pocztaruk et al., 2011). Christensen and Vickers (1981) found that consumers were still able to judge the crispness of 32 food samples in the presence of an auditory block (masking noise played via headphones). The results from that study implied that auditory information was not essential in the determination of food crispness. More recently, Demattè et al. (2014) found that the perceived crispness of apples was significantly lower when filtered reductions were applied (−12 dB or by −24 dB) than when no filter (0 dB) was used. However, Demattè et al. noted that an additional reduction of the sound information available during apple evaluation did not result in a further decrease in its perceived crispness. This could be related to the nature of the sound manipulations adopted by Demattè and colleagues. When the frequencies typical of crisp foods are filtered, a reduction in that perception is observed, while when the sound information is severely reduced (including more frequencies than only those classically associated to crispness) no additional effect is observed i.e., once the crucial information is altered, a floor effect is reached and no further decrease in crispness intensity is obtainable (Demattè et al. 2014). This floor effect could explain the fact that even though individuals with hearing loss were not able to discriminate small differences in crispness, they were still able to discriminate samples with larger crispness variations.

Other authors have attempted to simulate hearing loss by means of ear occlusion in an effort to understand the relationship between this sensory disorder and sensory perception and acceptance of food. Jutras et al. (2019), with the purpose of mimicking conductive hearing loss, occluded participants ear canals and asked consumers to taste soft and crispy foods and further evaluate the samples in terms of freshness and acceptance. The authors found no significant differences in the sensory perception or acceptance of food samples, regardless of crispness intensity, between the unplugged and plugged ear conditions. Jutras (2019) also found that sound mastication levels were higher when the ear was blocked compared to when it was unplugged, indicating that the samples may have appeared louder to the subjects when their ears were plugged (perceived loudness was not measured by the authors). While employing noise blocks or earplugs certainly adds to the body of knowledge on the role of auditory cues on modulating crispness perception, some issues may arise with this methodology if the intention is to simulate hearing loss. For example, the use of earplugs is commonly associated with an increased perception of the bone-conducted part of one's physiological noise, including bone-conducted chewing sounds, a phenomenon often referred to as the occlusion effect (Carillo et al., 2006). This phenomenon may explain why Jutras et al. obtained higher mastication sound levels in the ear-occluded condition compared to the unplugged condition. Moreover, blocking the ear canal fails to consider other alterations that may occur at the inner ear, nerve, brain, or neuronal level implicated in some types of hearing loss (i.e., sensorineural hearing loss).

Overall acceptance of solid food samples was lower for the group with hearing loss compared to the group with normal hearing, especially for samples with higher crispness intensity such as that of melba toast. Further regression analysis revealed a negative relationship between pitch and overall liking for the individuals with hearing loss, but not for the individuals with normal hearing. Sounds generated by crispy foods are high-pitched (especially the air conduction). They have a low level of bone conduction, which emphasizes the perception of high pitch (Dacremont, 1995). As mentioned before, the perception of food texture involves not only oral sensation but also auditory feedback. It might be therefore possible to alter people's experience of food texture due to the lack of auditory feedback of chewing sounds, thereby ameliorating dissatisfaction with food texture in individuals with hearing loss. Textural properties of food are used by consumers as key quality indicators that contribute to product acceptability (Duizer 2001). Particularly, crispness has shown to be one of the most important textural attributes impacting consumer acceptability (Szczesniak, 1990). This occurs due to consumers expectations of a crisp product to produce a sound upon biting and if it does not, then it is considered to be stale and of poor quality or has been produced using inappropriate ingredients or processes (Duizer, 2001).

Emotions such as anger and arousal expressed in facial expressions were also impacted by hearing status. Congruent with the lower acceptance data, the sample melba toast elicited a higher negative emotion of anger for the group with hearing loss. In addition, individuals with hearing loss exhibited higher arousal scores when considering all samples compared to the group with normal hearing. Since negative emotions such as anger and fear have higher valence and arousal dimensions (Gilet & Jallais, 2011) it is not surprising to see anger and arousal simultaneously increasing. Anger emotion in food consumer behaviour research has been previously related to dissatisfaction with the food product, food quality concerns, and food safety fears (Jin et al., 2020; Walsh et al., 2017). Emotional responses toward food have shown to be accurate predictors of consumer acceptance and they help to better understand consumer preferences toward specific products (Samant & Seo, 2019; Gutjar et al., 2015). Indeed, Samant and Seo (2019) found that a combination of sensory intensities and emotions increased liking predictability in food products like vegetable juice. Thus, the employment of emotional implicit measures would further add to the understanding of individuals with hearing loss food preferences and behaviour.

4.2 Hearing loss impacted loudness or viscosity discrimination of liquid food samples

The present study shows that individuals with hearing loss perceived the liquid samples to be less loud than individuals with normal hearing. To best our knowledge, this study is the first one to demonstrate an impact of hearing loss on loudness perception of liquid food samples during swallowing. In a similar manner to solid foods, the lack of feedback coming specifically from bone-conductive sounds generated during swallowing liquid foods could have impacted the subjective loudness in this group. Moreover, viscosity perception was also impacted by the hearing loss. It was observed that the individuals with hearing loss were not sensitive to the differences in viscosity between condensed milk and chocolate syrup. Auditory contributions of liquid food samples, even though less explored than solids, have also shown to be of great significance in the perception of viscosity and mouthfeel-related attributes (e.g., creaminess, oiliness, or carbonation, etc) attributes. For example, Velasco et al. showed consumers were able to detect auditory changes in water poured into a variety of vessels at different temperatures (Velasco et al., 2013, Velasco et al., 2016). In these studies, participants were presented with pre-recorded audio of water being poured into different vessels and asked to correctly identify if the water was hot or cold. People were not only able to detect differences above chance but in follow-up studies were aware of the differences in pitch and tempo (Wang & Spence, 2017). In another study, Pellegrino et al. (2019) found that consumers were able to more accurately discriminate milk samples of varying viscosities by listening to the samples pouring and by consuming the samples rather than by visual inspection, indicating that the sense of hearing and oral tactile sensations are more sensitive to changes in viscosity. It is important to note that most of the research on the impacts of sound cues on sensory perception of liquid foods has taken an auditory approach (pre-recorded sounds are played for evaluation) and not an oral approach (responses are gathered during swallowing). Previous research has demonstrated that liquid foods with different viscosities produce different acoustic swallowing profiles (Reimers-Neils, 1994; Youmans & Stierwalt, 2011; Feng et al., 2021). However, there is no general agreement on the nature of the relationship between sound intensity and viscosity. Feng et al. (2021) results showed that thinner liquids produced higher loudness than more viscous liquids. In contrast, other studies have shown no significant relationship between swallowing sounds and liquid consistencies (Reimers-Neils,1994; Jestrović et al., 2013). Previous research on the multimodal relationship between sound and perceived liquid viscosity found that low viscosity was paired with high-pitch pure tones, but the inverse associations (i.e., high viscosity with low pitch) were not significant (Asad et al., 2016). In this study, however, the loudness of liquid samples was perceived as higher for individuals with normal hearing as viscosity increased.

Hearing loss had little impact on the acceptance and facial expression-based emotions of liquid food samples with varying levels of viscosity. Regression analysis found that both hearing groups associated higher viscosities with lower acceptance scores. One explanation for these results may lie in the age group of our sample population. Hearing loss is more prevalent among older adults, with two-thirds of individuals aged 70 years or older having bilateral hearing loss and almost three-quarters having hearing loss in at least one ear (Goman & Lin, 2016). Thus, it is not surprising that the large majority of our sample was within this age group. Previous research has shown that as age increases our sensitivity to texture attributes in food may decrease, further impacting acceptance (Whiters et al., 2013; Heiniö & Pentikäinen, 2014). For example, Kremer et al. (2005) found that older adults' perception of creaminess was lower compared to young adults' creaminess perception. Similarly, Smith et al. (2006) found that viscosity perception deteriorates with increasing age. Along with the decrease in oral tactile sensitivity, higher viscosities in liquids have been associated with a perceived difficulty in swallowing in older adults (Park et al., 2020; Humbert & Robins, 2008). Excessively viscous food requires much more force on the tongue and pharynx during swallowing which could have impacted consumers overall acceptance (Park et al., 2020).

5. Conclusions

The importance of understanding the impacts of sensory disorders in the acceptance and perception of food cannot be underestimated. Hearing loss has been particularly overlooked and not much was understood on the impacts that this disorder may have in food enjoyment and perception. Results from this research show associations between hearing loss and changes in the texture perception and acceptance of solid and liquid food samples. A reduced loudness perception of both solid and liquid food samples was observed in the group with hearing loss. Furthermore, hearing-loss reduced the sensitivity to discriminate solid samples with smaller differences in crispness and liquid samples with larger differences in viscosity. The impacts of a hearing loss were also observed in a decrease of the overall acceptance of solid food samples, explained possibly by the absence of auditory feedback that comes with a hearing loss. Sensory professionals and food developers could benefit from these results and promote the creation of food products with sensory characteristics that satisfy the accrescent population with hearing losses.

Table 1. Demographic profile of participants.

	Group with Normal Hearing		Group with Hearing Loss	
	N	%	*N*	%
Number of Participants	37		37	
Gender				
Men	19	51.4	20	54.1
Women	18	48.6	17	45.9
Mean Age (± Standard Deviation)	58.0 (± 12.8)		62.0 (± 13.1)	
Education Level[1]				
High school	4	10.8	5	13.5
Some college	6	16.2	11	29.7
2–4 year college degree	12	32.4	7	18.9
Master, or PhD degree	15	40.5	14	37.8
Annual Income (per year)				
<$20,000	3	8.1	3	8.1
$20,000 to $39,999	5	13.5	7	18.9
$40,000 to $59,999	7	18.9	8	21.6
$60,000 to $79,999	9	24.3	6	16.2
$80,000 to $99,999	11	29.7	6	16.2
>$100,000	2	5.4	7	18.9
Type of Hearing Loss				
Conductive			8	21.6
Sensorineural			17	45.9
Mixed (conductive and sensorineural)			6	16.2
Other			6	16.2
Degree of Hearing Loss				
Mild			6	16.2
Moderate			9	24.3
Moderately Severe			10	27.0
Severe			4	10.8
Profound			4	10.8
Other			4	10.8
Configuration of Hearing Loss				
High Frequency			20	54.1
Middle Frequency			6	16.2
Low Frequency			6	16.2
Other			5	13.5
Hearing Assistive (HA) Device Usage				
Hearing aids			18	48.6
Cochlear implants			1	2.7
Do not wear a HA device			18	48.6

[1]Two categories of education level, “master degree” and “doctoral or professional degree”, were combined since the number of each case was small.

Table 2. Solid and liquid food samples employed on this study.

	Spectrum Scale Value[1]	Food Sample	Brand	Tasting Stage
Solid Food Samples Crispness	2.0	Granola Bar	Quaker (Chicago, IL, USA)	Large differences
	5.0	Club Cracker	Kellogg's (Battle Creek, MI, USA)	Small differences
	7.0	Oat Cereal	Kellogg's (Battle Creek, MI, USA)	Small and large differences
	17.0	Melba Toast	Devonsheer (Parsippany-Troy Hills, NJ, USA)	Large differences
Liquid Food Samples Viscosity	2.0	Half & Half	Great Value (Bentonville, AR, USA)	Large differences
	4.0	Heavy Cream	Great Value (Bentonville, AR, USA)	Small differences
	6.0	Maple Syrup	Maple Grove Farms (Connersville, IN, USA)	Small differences
	9.0	Chocolate Syrup	Hershey's (Derry Township, PA, USA)	Large differences
	14.5	Sweetened Condensed Milk	Eagle Brand (El Paso, TX, USA)	Large differences

[1] Meilgaard, M., Civille, G.V. and Carr, B.T. 2015. Sensory Evaluation Techniques (5th Ed.). CRC Press, Boca Raton, Florida.

Table 3. Mean ratings (± standard deviation) of each solid food sample evaluated by either individuals with normal hearing or with hearing loss with respect to sensory perception and hedonic impression, and *P*-values associated with hearing group effect, food sample effect and hearing group and food sample interaction.

	Sample	Crispness Intensity[a]	Loudness Intensity	Pitch Intensity	Overall Liking
Group with Normal Hearing	Granola Bar	42.10c (± 18.31)	44.36de (± 15.23)	40.34de (± 16.77)	6.28abc (± 2.07)
	Club Cracker	68.79b (± 13.90)	61.91bc (± 14.10)	54.80c (± 16.49)	6.90ab (± 1.77)
	Oat Cereal	75.09b (± 15.86)	67.99b (± 18.32)	58.67bc (± 19.65)	6.33abc (± 1.88)
	Melba Toast	90.59a (± 11.43)	83.64a (± 16.92)	73.96a (± 20.51)	5.55cd (± 2.15)
Group with Hearing Loss	Granola Bar	40.66c (± 16.40)	40.75e (± 15.19)	41.48e (± 17.29)	6.55abc (± 1.85)
	Club Cracker	68.65b (± 15.59)	53.68cd (± 13.19)	49.62cde (± 15.04)	7.28a (± 1.60)
	Oat Cereal	68.05b (± 18.24)	59.58bc (± 16.16)	52.90cd (± 17.06)	5.65bcd (± 1.95)
	Melba Toast	88.29a (± 12.89)	81.30a (± 13.78)	68.91ab (± 21.25)	4.55d (± 2.07)
Hearing Group Effect	*P*-value	0.25	0.02	0.21	0.38
Food Sample Effect	*P*-value	<0.001	<0.001	<0.001	<0.001
Hearing Group x Food Sample Interaction	*P*-value	0.44	0.4	0.46	0.03

[a] Mean ratings with different letters within a column represent a significant difference determined by *post hoc* *t*-tests.

Table 4. Rank sum data, *P*-values and multiple comparison groupings for solid samples ranking test.

		Group with Normal Hearing		Group with Hearing Loss	
	Sample	**Rank sum**	***P*-value**	**Rank sum**	***P*-value**
Solid food with smaller differences in crispness	Club cracker	48.0b	0.014	50.0a	0.071
	Oat cereal	63.0a		61.0a	
Solid food with larger differences in crispness	Granola bar	38.0c	<0.001	42.0c	<0.001
	Oat cereal	73.0b		73.0b	

Within a cell, rank sums with different letters within a colum represent a significant difference determined by Conover tests.

Table 5. Mean ratings (± standard deviation) of each liquid food sample evaluated by either individuals with normal hearing or with hearing loss with respect to sensory perception and hedonic impression, and *P*-values associated with hearing group effect, food sample effect and hearing group and food sample interaction.

	Sample	**Viscosity Intensity[a]**	**Loudness Intensity**	**Overall Liking**
Group with Normal Hearing	Half & Half	40.45e (± 17.84)	37.9d (± 20.82)	6.35a (± 1.86)
	Heavy Cream	68.84cd (± 18.07)	40.24cd (± 21.03)	5.35abc (± 2.31)
	Maple Syrup	85.79ab (± 13.75)	48.67abc (± 27.45)	4.27c (± 2.58)
	Chocolate Syrup	84.47ab (± 13.14)	51.91ab (± 28.69)	5.92ab (± 2.02)
	Condensed Milk	92.07a (± 15.55)	42.15a (± 31.64)	4.54bc (± 2.61)
Group with Hearing Loss	Half & Half	42.50e (± 18.85)	34.85bcd (± 19.17)	5.49abc (± 1.73)
	Heavy Cream	68.33d (± 19.00)	36.92abcd (± 19.54)	4.68abc (± 2.24)
	Maple Syrup	79.59bc (± 14.97)	36.65abcd (± 21.4)	4.76abc (± 2.43)
	Chocolate Syrup	84.63ab (± 12.23)	38.77abcd (± 22.38)	5.54abc (± 2.44)
	Condensed Milk	92.07a (± 15.49)	42.15abcd (± 24.04)	4.54bc (± 2.41)
Hearing Group Effect	*P*-value	0.58	0.08	0.38
Food Sample Effect	*P*-value	<0.001	<0.001	<0.001
Hearing Group x Food Sample Interaction	*P*-value	0.50	0.04	0.22

[a] Mean ratings with different letters within a column represent a significant difference determined by *post hoc* *t*-tests.

Table 6. Rank sum data, *P*-values and multiple comparison groupings for liquid samples ranking test.

		Group with Normal Hearing		Group with Hearing Loss	
	Sample	**Rank sum**	***P*-value**	**Rank sum**	***P*-value**
Liquid foods with smaller differences in viscosity	Heavy Cream	41.0b	<0.001	41.0b	<0.001
	Maple Syrup	70.0a		70.0a	
Liquid foods with larger differences in viscosity	Half & Half	38.0a	<0.001	37.0a	<0.001
	Chocolate Syrup	78.0b		76.0b	
	Condensed Milk	106.0c		109.0c	

Within a cell, rank sums with different letters within a colum represent a significant difference determined by Conover tests.

Supplementary Table 1. Mean ratings (± standard deviation) of each solid food sample evaluated by either individuals with normal hearing or with hearing loss with respect to facial expressions-based emotions, and *P*-values associated with hearing group effect, food sample effect and hearing group and food sample interaction

	Sample	Neutral[a]	Happy	Sad	Angry	Surprised	Scared	Disgusted	Valence	Arousal
Group with Normal Hearing	Granola Bar	-0.08 (± 0.17)	-0.01 (± 0.03)	0.00 (± 0.12)	0.03abc (± 0.09)	0.00 (± 0.03)	0.00 (± 0.02)	0.02 (± 0.08)	-0.04 (± 0.11)	0.00bc (± 0.07)
	Club Cracker	-0.06 (± 0.16)	0.00 (± 0.02)	-0.01 (± 0.11)	0.01bc (± 0.09)	-0.02 (± 0.08)	0.00 (± 0.01)	0.02 (± 0.09)	0.01 (± 0.13)	-0.03c (± 0.07)
	Oat Cereal	-0.08 (± 0.17)	0.00 (± 0.05)	-0.03 (± 0.12)	0.04abc (± 0.11)	0.00 (± 0.03)	0.00 (± 0.01)	0.04 (± 0.09)	-0.03 (± 0.15)	0.00c (± 0.07)
	Melba Toast	-0.13 (± 0.15)	0.00 (± 0.03)	-0.01 (± 0.12)	0.07a (± 0.13)	0.00 (± 0.04)	0.00 (± 0.01)	0.04 (± 0.07)	-0.07 (± 0.11)	0.02c (± 0.07)
Group with Hearing Loss	Granola Bar	-0.10 (± 0.15)	0.00 (± 0.06)	0.01 (± 0.08)	0.04abc (± 0.15)	0.01 (± 0.04)	0.00 (± 0.01)	0.03 (± 0.08)	-0.04 (± 0.15)	-0.03ab (± 0.08)
	Club Cracker	-0.07 (± 0.13)	0.01 (± 0.02)	0.01 (± 0.09)	0.06ab (± 0.14)	0.00 (± 0.04)	0.00 (± 0.01)	-0.01 (± 0.13)	-0.01 (± 0.14)	-0.04c (± 0.10)
	Oat Cereal	-0.05 (± 0.13)	0.00 (± 0.02)	0.01 (± 0.09)	0.03abc (± 0.12)	-0.01 (± 0.05)	0.00 (± 0.02)	0.02 (± 0.13)	-0.01 (± 0.15)	-0.05ab (± 0.07)
	Melba Toast	-0.09 (± 0.14)	0.01 (± 0.03)	0.00 (± 0.11)	0.01c (± 0.13)	0.01 (± 0.04)	0.00 (± 0.01)	0.03 (± 0.08)	0.00 (± 0.15)	-0.04a (± 0.10)
Hearing Group Effect	*P*-value	0.73	0.20	0.28	0.79	0.48	0.33	0.39	0.45	0.01
Food Sample Effect	*P*-value	0.06	0.52	0.69	1.00	0.31	0.49	0.08	0.13	0.05
Hearing Group x Food Sample Interaction	*P*-value	0.31	0.97	0.46	0.01	0.11	0.68	0.46	0.14	0.13

[a] Mean ratings with different letters within a column represent a significant difference determined by Student's tests.

Supplementary Table 2. Mean ratings (± standard deviation) of each liquid food sample evaluated by either individuals with normal hearing or with hearing loss with respect to facial expressions-based emotions, and *P*-values associated with hearing group effect, food sample effect and hearing group and food sample interaction.

	Sample	**Neutral**	**Happy**	**Sad**	**Angry**	**Surprised**	**Scared**	**Disgusted**	**Valence**	**Arousal**
Group with Normal Hearing	Half & Half	-0.01 (± 0.13)	0.00 (± 0.04)	-0.02 (± 0.12)	-0.01 (± 0.08)	0.00 (± 0.04)	0.00 (± 0.01)	0.01 (± 0.06)	0.02 (± 0.13)	-0.02 (± 0.09)
	Maple Syrup	-0.10 (± 0.16)	0.03 (± 0.06)	-0.01 (± 0.15)	0.02 (± 0.13)	0.00 (± 0.03)	0.00 (± 0.02)	0.03 (± 0.11)	0.01 (± 0.14)	0.01 (± 0.07)
	Heavy Cream	-0.11 (± 0.18)	0.01 (± 0.03)	0.01 (± 0.10)	0.03 (± 0.09)	-0.01 (± 0.04)	0.00 (± 0.01)	0.02 (± 0.12)	-0.02 (± 0.14)	0.00 (± 0.08)
	Chocolate Syrup	-0.09 (± 0.16)	0.00 (± 0.03)	-0.03 (± 0.12)	0.01 (± 0.11)	0.01 (± 0.02)	0.00 (± 0.01)	0.03 (± 0.09)	0.00 (± 0.13)	-0.01 (± 0.10)
	Condensed Milk	-0.08 (± 0.21)	0.02 (± 0.06)	-0.03 (± 0.17)	0.03 (± 0.12)	0.00 (± 0.02)	0.00 (± 0.01)	0.03 (± 0.11)	0.03 (± 0.19)	-0.01 (± 0.09)
Group with Hearing Loss	Half & Half	-0.05 (± 0.13)	0.00 (± 0.06)	0.01 (± 0.14)	0.02 (± 0.08)	-0.02 (± 0.06)	0.00 (± 0.01)	0.03 (± 0.08)	-0.02 (± 0.17)	-0.03 (± 0.10)
	Maple Syrup	-0.17 (± 0.16)	0.02 (± 0.04)	0.01 (± 0.13)	0.01 (± 0.13)	0.01 (± 0.03)	0.00 (± 0.01)	0.05 (± 0.11)	-0.03 (± 0.18)	0.01 (± 0.08)
	Heavy Cream	-0.14 (± 0.14)	0.02 (± 0.04)	0.03 (± 0.09)	0.01 (± 0.12)	0.00 (± 0.05)	0.00 (± 0.01)	0.04 (± 0.10)	-0.02 (± 0.15)	0.00 (± 0.10)
	Chocolate Syrup	-0.06 (± 0.20)	0.02 (± 0.03)	-0.01 (± 0.13)	0.00 (± 0.15)	0.02 (± 0.04)	0.00 (± 0.01)	0.02 (± 0.08)	0.04 (± 0.18)	-0.02 (± 0.11)
	Condensed Milk	-0.11 (± 0.16)	0.02 (± 0.03)	-0.02 (± 0.15)	0.00 (± 0.13)	0.00 (± 0.06)	0.00 (± 0.01)	0.05 (± 0.10)	0.02 (± 0.18)	-0.02 (± 0.09)
Hearing Group Effect	*P*-value	0.38	0.69	0.35	0.73	0.47	0.71	0.28	0.61	0.66
Food Sample Effect	*P*-value	<0.001	0.00	0.13	0.86	0.00	0.46	0.52	0.21	0.04
Hearing Group x Food Sample Interaction	*P*-value	0.25	0.42	1.00	0.49	0.07	0.63	0.71	0.38	0.92

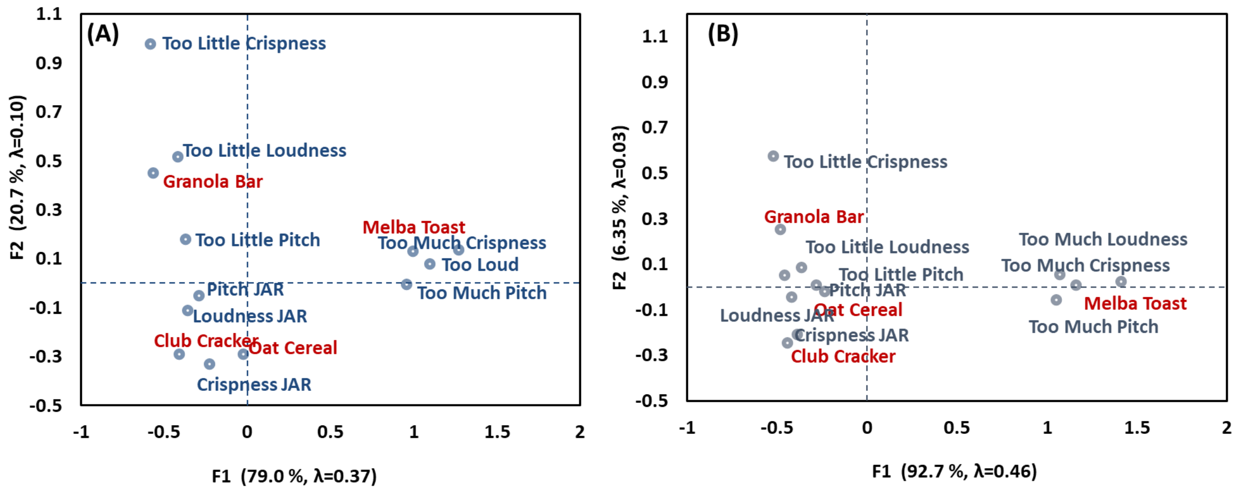

Figure 1. A bi-plot of correspondence analysis (CA) based on JAR scores of the four solid foods evaluated by (A) group with normal hearing or (B) group with hearing loss. The bi-plots of CA for the individuals with normal hearing and with hearing loss accounted for 99.7% and 99.05% of the total variance, respectively.

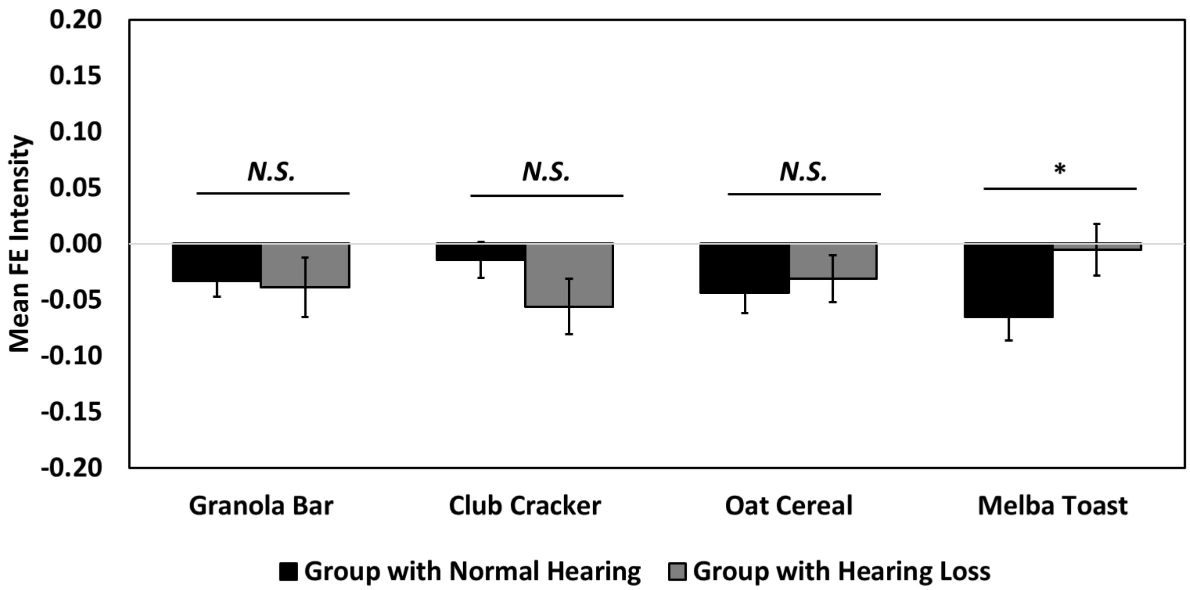

Figure 2. Interactions between "hearing group" and "food sample" with respect to "angry" facial expression (FE) intensity toward four solid food samples. * represent a significant difference at $P < 0.05$. *N.S.* represents no significant difference at $P < 0.05$. Error bars represent standard error of the means.

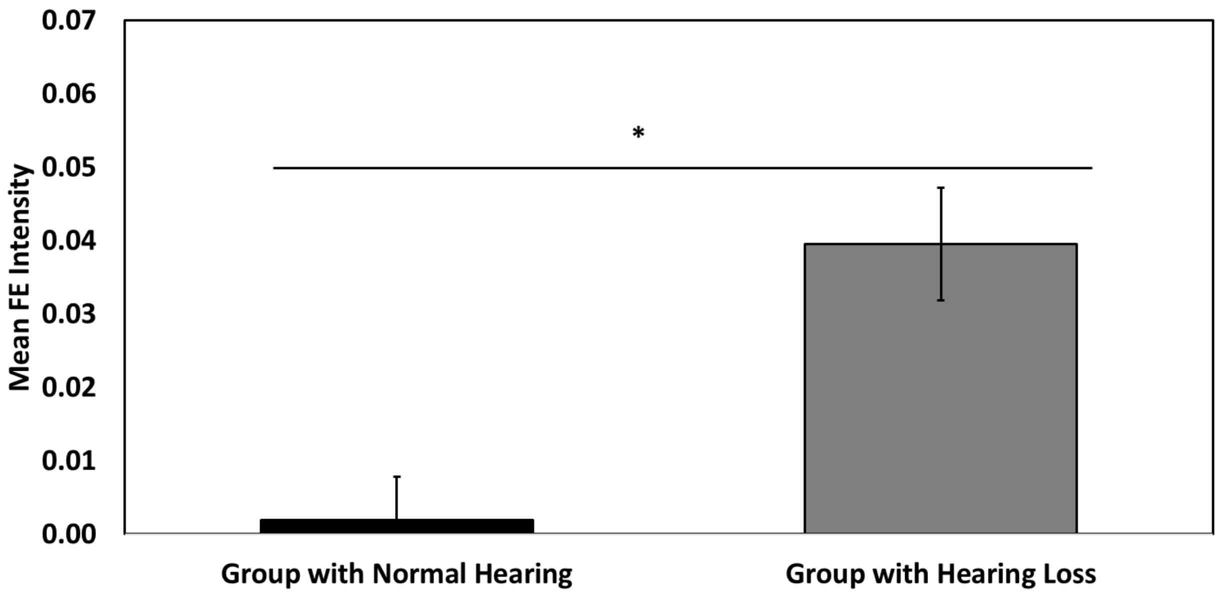

Figure 3. **Effect of hearing group on the intensity of "arousal" facial expression (FE) toward four solid food samples**. * represent a significant difference at $P < 0.05$. Error bars represent standard error of the means.

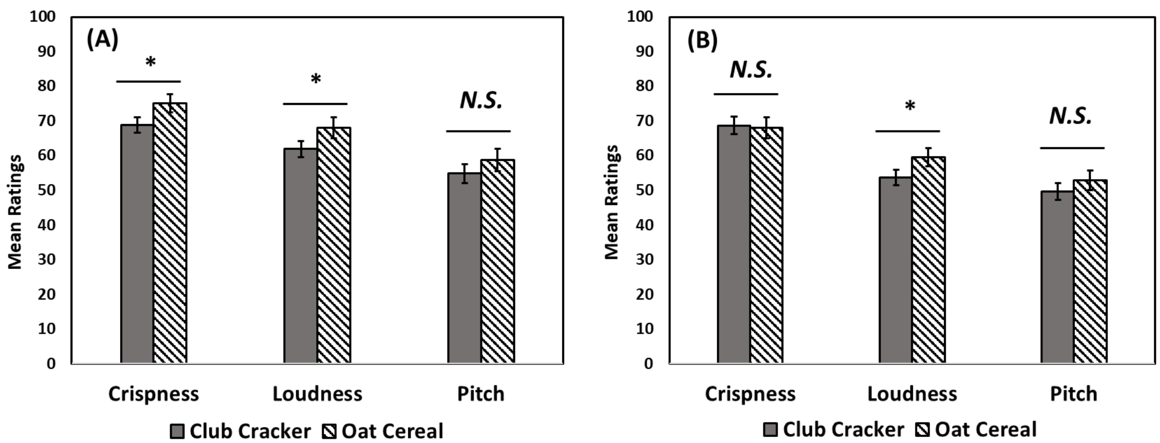

Figure 4. Sensory ratings of solid samples with smaller differences in crispness evaluated by (A) group with normal hearing or (B) group with hearing loss. * represent a significant difference at $P < 0.05$. *N.S.* represents no significant difference at $P < 0.05$. Error bars represent standard error of the means.

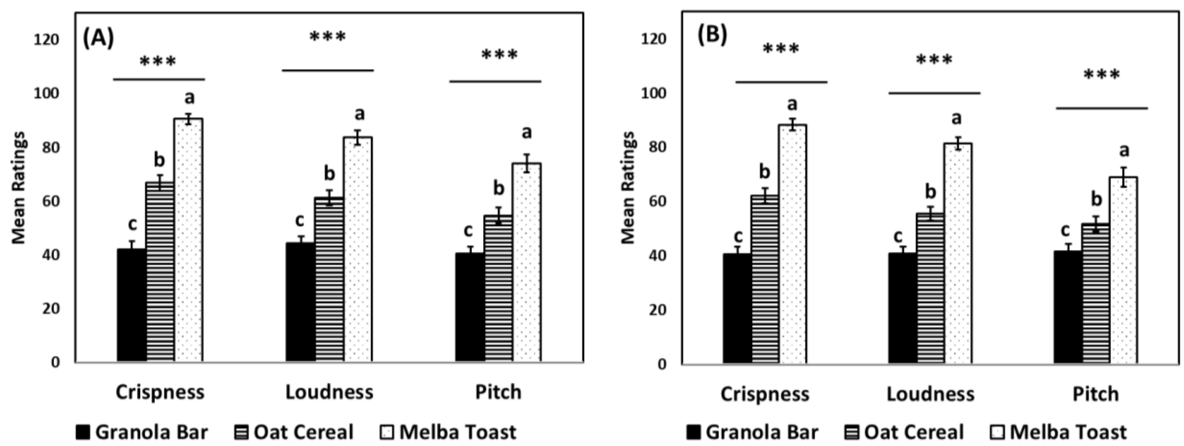

Figure 5. Sensory ratings of solid samples with larger differences in crispness evaluated by (A) group with normal hearing or (B) group with hearing loss. *** represent a significant difference at $P < 0.001$. The ratings with different letters within one category are significantly different at $P < 0.05$. Error bars represent standard error of the means.

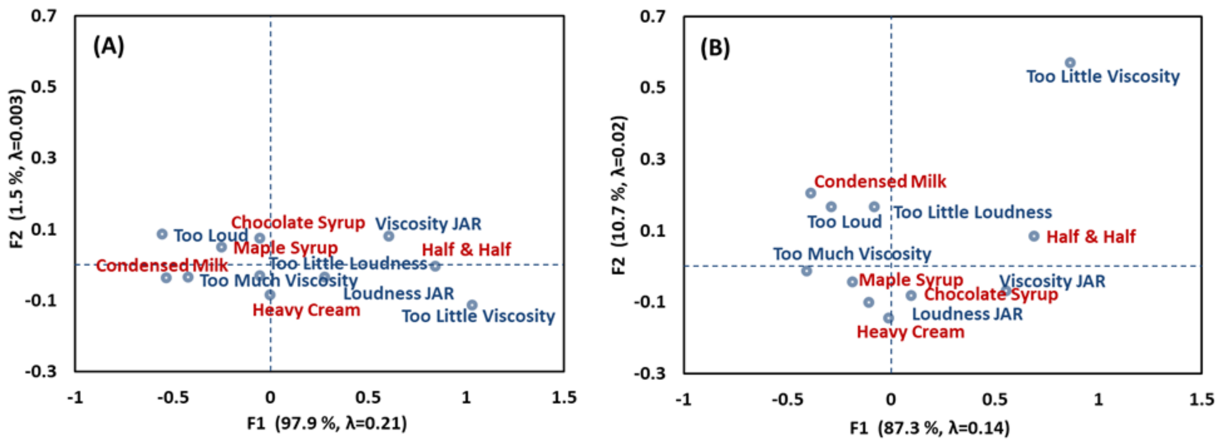

Figure 6. A bi-plot of correspondence analysis (CA) based on JAR scores of the five liquid foods evaluated by (A) group with normal hearing or (B) group with hearing loss. The bi-plots of CA for individuals with normal hearing and with hearing loss accounted for 99.4% and 98.00% of the total variance, respectively.

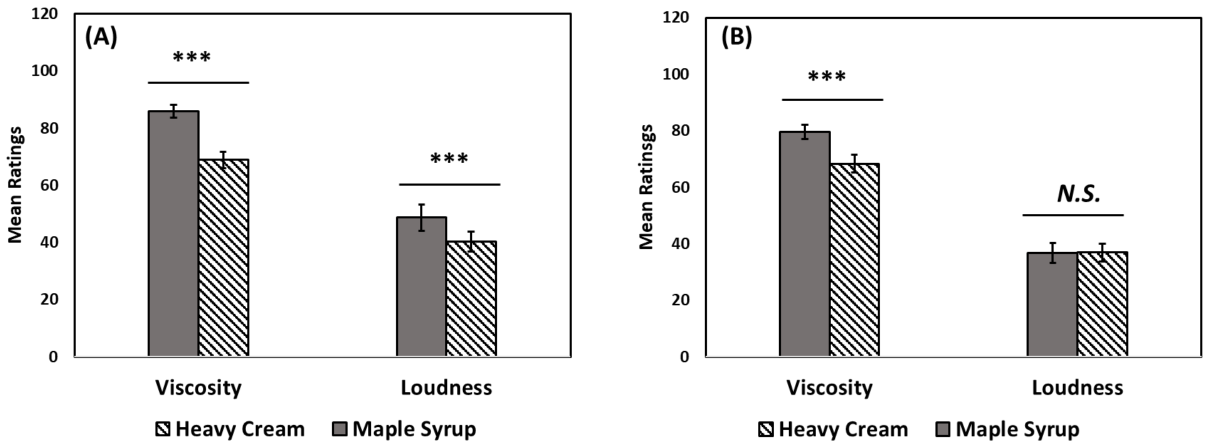

Figure 7. Sensory ratings of liquid samples with smaller differences in viscosity evaluated by (A) group with normal hearing or (B) group with hearing loss. *** represent a significant difference at $P < 0.001$. *N.S*. represents no significant difference at $P < 0.05$. Error bars represent standard error of the means.

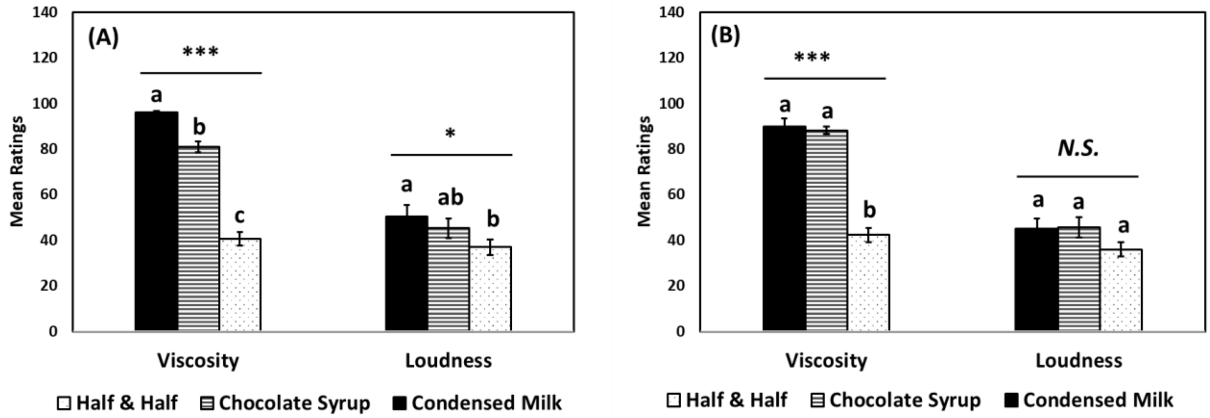

Figure 8. Sensory ratings of liquid samples with larger differences in viscosity evaluated by (A) group with normal hearing or (B) group with hearing loss. *, *** represent a significant difference at $P < 0.05$ and at $P < 0.001$, respectively. *N.S.* represents no significant difference at $P < 0.05$. The ratings with different letters within one category are significantly different at $P < 0.05$. Error bars represent standard error of the means.

References

American Speech-Language-Hearing Association. (2022). *Adult hearing screening*. Rockville, MD : American Speech-Language-Hearing Association. www.asha.org/Practice-Portal/Professional-Issues/Adult-Hearing-Screening/.

Asad, J., Spiller, M. J., & Jonas, C. (2016). Auditory and visual crossmodal correspondences with haptically perceived liquid viscosity. *Multisensory Research, 29*(8), 727-747. https://doi.org/10.1163/22134808-00002534

Bach, P. J., & Schaefer, J. M. (1979). The tempo of country music and the rate of drinking in bars. *Journal of Studies on Alcohol, 40*(11), 1058-1059. https://doi.org/10.15288/jsa.1979.40.1058

Brockhoff, P. B., & Linander, C. B. (2017). Analysis of the data using the r package sensR. In L. Rogers (Ed.), *Discrimination Testing in Sensory Science* (pp. 303-344). Woodhead Publishing. https://doi.org/10.1016/b978-0-08-101009-9.00015-0

Bronner, K., Bruhn, H., Hirt, R., & Piper, D. (2008). Research on the interaction between the perception of music and flavour. 9th Annual Meeting of the International Multisensory Research Forum (IMRF), Hamburg, Germany,

Bronner, K., Hirt, R., & Ringe, C. (2013). Audio branding academy yearbook. Baden-Baden.

Brown, R. L. (1958). Wrapper influence on the perception of freshness in bread. *Journal of Applied Psychology, 42*(4), 257-260. https://doi.org/10.1037/h0046879

Calvert, G., Spence, C., & Stein, B. E. (2004). *The handbook of multisensory processes*. MIT press.

Carillo, K., Doutres, O., & Sgard, F. (2021). Numerical investigation of the earplug contribution to the low-frequency objective occlusion effect induced by bone-conducted stimulation. *The Journal of the Acoustical Society of America, 150*(3), 2006. https://doi.org/10.1121/10.0006209

Chapko, M. J., & Seo, H. S. (2019). Characterizing product temperature-dependent sensory perception of brewed coffee beverages: Descriptive sensory analysis. *Food Res Int, 121*, 612-621. https://doi.org/10.1016/j.foodres.2018.12.026

Christensen, C. M., & Vickers, Z. M. (1981). Relationships of chewing sounds to judgments of food crispness. *Journal of Food Science, 46*(2), 574-578. https://doi.org/10.1111/j.1365-2621.1981.tb04914.x

Civille, G. V., & Carr, B. T. (2015). *Sensory evaluation techniques*. CRC Press.

Crisinel, A. S., & Spence, C. (2009). Implicit association between basic tastes and pitch. *Neuroscience Letters, 464*(1), 39-42. https://doi.org/10.1016/j.neulet.2009.08.016

Dacremont, C. (1995). Spectral composition of eating sounds generated by crispy, crunchy and crackly foods. *Journal of texture studies, 26*(1), 27-43.

Danner, L., Sidorkina, L., Joechl, M., & Duerrschmid, K. (2014). Make a face! Implicit and explicit measurement of facial expressions elicited by orange juices using face reading technology. *Food Quality and Preference, 32*, 167-172. https://doi.org/10.1016/j.foodqual.2013.01.004

de Liz Pocztaruk, R., Abbink, J. H., de Wijk, R. A., da Fontoura Frasca, L. C., Gavião, M. B. D., & van der Bilt, A. (2011). The influence of auditory and visual information on the perception of crispy food. *Food Quality and Preference*, *22*(5), 404-411. https://doi.org/10.1016/j.foodqual.2010.11.008

de Wijk, R. A., He, W., Mensink, M. G., Verhoeven, R. H., & de Graaf, C. (2014). ANS responses and facial expressions differentiate between the taste of commercial breakfast drinks. *PLOS ONE*, *9*(4), e93823. https://doi.org/10.1371/journal.pone.0093823

Demattè, M. L., Pojer, N., Endrizzi, I., Corollaro, M. L., Betta, E., Aprea, E., Charles, M., Biasioli, F., Zampini, M., & Gasperi, F. (2014). Effects of the sound of the bite on apple perceived crispness and hardness. *Food Quality and Preference, 38*, 58-64. https://doi.org/10.1016/j.foodqual.2014.05.009

Drake, B. K. (1963). Food crushing sounds. An introductory study. *Journal of Food Science, 28*(2), 233-241. https://doi.org/10.1111/j.1365-2621.1963.tb00190.x

Duizer, L. (2001). A review of acoustic research for studying the sensory perception of crisp, crunchy and crackly textures. *Trends in Food Science & Technology, 12*(1), 17-24. https://doi.org/10.1016/s0924-2244(01)00050-4

Eggermont, J. J. (2013). *Noise and the brain: experience dependent developmental and adult plasticity*. Academic Press.

Feng, C., Volkman, K., Wagoner, C., & Siu, K. C. (2022). Effects of different viscous liquids and solid foods on swallowing speeds and sounds among healthy adults. *International Journal of Language & Communication Disorders, 57*(1), 78-89. https://doi.org/10.1111/1460-6984.12675

Ferris, A. M., & Duffy, V. B. (1989). Effect of olfactory deficits on nutritional status. Does age predict persons at risk? *Annals of the New York Academy of Sciences, 561*, 113-123. https://doi.org/10.1111/j.1749-6632.1989.tb20975.x

Gilet, A.-L., & Jallais, C. (2011). Valence, arousal, and word associations. *Cognition and Emotion*, *25*(4), 740-746. https://doi.org/10.1080/02699931.2010.500480

Goman, A. M., & Lin, F. R. (2016). Prevalence of hearing loss by severity in the united states. *American Journal of Public Health, 106*(10), 1820-1822. https://doi.org/10.2105/AJPH.2016.303299

Gueguen, N., Jacob, C., Le Guellec, H., Morineau, T., & Lourel, M. (2008). Sound level of environmental music and drinking behavior: a field experiment with beer drinkers. *Alcoholism: Clinical and Experimental Research, 32*(10), 1795-1798. https://doi.org/10.1111/j.1530-0277.2008.00764.x

Gunaratne, T. M., Fuentes, S., Gunaratne, N. M., Torrico, D. D., Gonzalez Viejo, C., & Dunshea, F. R. (2019). Physiological responses to basic tastes for sensory evaluation of chocolate using biometric techniques. *Foods, 8*(7), 243. https://doi.org/10.3390/foods8070243

Gutjar, S., Dalenberg, J. R., de Graaf, C., de Wijk, R. A., Palascha, A., Renken, R. J., & Jager, G. (2015). What reported food-evoked emotions may add: A model to predict consumer food choice. *Food Quality and Preference, 45*, 140-148.

Haile, L. M., Kamenov, K., Briant, P. S., Orji, A. U., Steinmetz, J. D., Abdoli, A., Abdollahi, M., Abu-Gharbieh, E., Afshin, A., Ahmed, H., Ahmed Rashid, T., Akalu, Y., Alahdab, F., Alanezi, F. M., Alanzi, T. M., Al Hamad, H., Ali, L., Alipour, V., Al-Raddadi, R. M., …Chadha, S. (2021). Hearing loss prevalence and years lived with disability, 1990–2019: findings from the Global Burden of Disease Study 2019. *The Lancet, 397*(10278), 996-1009. https://doi.org/https://doi.org/10.1016/S0140-6736(21)00516-X

Heiniö, R.-L., Pentikäinen, Saara. (2014). *A trained senior panel - Implication in developing nutritious food for seniors.* European Conference on Sensory and Consumer Research, EuroSense 2014, Copenhagen, Denmark.

Humbert, I. A., & Robbins, J. (2008). Dysphagia in the elderly. *Physical Medicine and Rehabilitation Clinics of North America, 19*(4), 853-866, ix-x. https://doi.org/10.1016/j.pmr.2008.06.002

Isaacson, J. E., & Vora, N. M. (2003). Differential diagnosis and treatment of hearing loss. *American Family Physician, 68*(6), 1125-1132. https://www.ncbi.nlm.nih.gov/pubmed/14524400

Jacob, C. (2006). Styles of background music and consumption in a bar: An empirical evaluation. *International Journal of Hospitality Management, 25*(4), 716-720. https://doi.org/10.1016/j.ijhm.2006.01.002

Jestrovic, I., Dudik, J. M., Luan, B., Coyle, J. L., & Sejdic, E. (2013). The effects of increased fluid viscosity on swallowing sounds in healthy adults. *BioMedical Engineering OnLine, 12*(1), 90. https://doi.org/10.1186/1475-925X-12-90

Jin, H., Lin, Z., & McLeay, F. (2020). Negative emotions, positive actions: Food safety and consumer intentions to purchase ethical food in China. *Food Quality and Preference, 85*, 103981. https://doi.org/https://doi.org/10.1016/j.foodqual.2020.103981

Jutras, B., Luond, A., Honegger, F., Stieger, C., Hummel, T., & Welge-Lussen, A. (2019). Influence of external ear occlusion on food perception. *European Archives of Oto-Rhino-Laryngology, 276*(3), 889-895. https://doi.org/10.1007/s00405-019-05296-w

Kaneko, D., Hogervorst, M., Toet, A., van Erp, J. B. F., Kallen, V., & Brouwer, A. M. (2019). Explicit and implicit responses to tasting drinks associated with different tasting experiences. *Sensors, 19*(20), 4397. https://doi.org/10.3390/s19204397

Kapur, K. K. (1971). Frequency spectrographic analysis of bone conducted chewing sounds in persons with natural and artificial dentitions. *Journal of texture studies, 2*(1), 50-61. https://doi.org/10.1111/j.1745-4603.1971.tb00272.x

Kessler, S. J., Jiang, F., & Hurley, R. A. (2020). The state of automated facial expression analysis (afea) in evaluating consumer packaged beverages. *Beverages, 6*(2), 27. https://www.mdpi.com/2306-5710/6/2/27

Knöferle, K. (2012). Using customer insights to improve product sound design. *Marketing Review St. Gallen, 29*(2), 47-53. https://doi.org/10.1007/s11621-012-0124-7

Kremer, S., Mojet, J. O. S., & Kroeze, J. H. A. (2005). Perception of texture and flavor in soups by elderly and young subjects. *Journal of texture studies, 36*(3), 255-272. https://doi.org/10.1111/j.1745-4603.2005.00015.x

Laureati, M., Pagliarini, E., Calcinoni, O., & Bidoglio, M. (2006). Sensory acceptability of traditional food preparations by elderly people. *Food Quality and Preference, 17*(1-2), 43-52. https://doi.org/10.1016/j.foodqual.2005.08.002

Leitch, K. A., Duncan, S. E., O'Keefe, S., Rudd, R., & Gallagher, D. L. (2015). Characterizing consumer emotional response to sweeteners using an emotion terminology questionnaire and facial expression analysis. *Food Research International, 76*, 283-292. https://doi.org/10.1016/j.foodres.2015.04.039

Luckett, C. R., Meullenet, J.-F., & Seo, H.-S. (2016). Crispness level of potato chips affects temporal dynamics of flavor perception and mastication patterns in adults of different age groups. *Food Quality and Preference, 51*, 8-19. https://doi.org/10.1016/j.foodqual.2016.02.013

Meilgaard, M., Civille, G.V. and Carr, B.T. (2015). *Sensory Evaluation Techniques* (5 ed.). CRC Press.

Michels, T. C., Duffy, M. T., & Rogers, D. J. (2019). Hearing loss in adults: differential diagnosis and treatment. *American Family Physician, 100*(2), 98-108. https://www.ncbi.nlm.nih.gov/pubmed/31305044

Park, J. W., Lee, S., Yoo, B., & Nam, K. (2020). Effects of texture properties of semi-solid food on the sensory test for pharyngeal swallowing effort in the older adults. *BMC Geriatrics, 20*(1), 493. https://doi.org/10.1186/s12877-020-01890-4

Pellegrino, R., Jones, J. D., Shupe, G. E., & Luckett, C. R. (2019). Sensitivity to viscosity changes and subsequent estimates of satiety across different senses. *Appetite, 133*, 101-106. https://doi.org/10.1016/j.appet.2018.10.028

Reimers-Neils, L., Logemann, J., & Larson, C. (1994). Viscosity effects on EMG activity in normal swallow. *Dysphagia, 9*(2), 101-106. https://doi.org/10.1007/BF00714596

Saitoh, E., Shibata, S., Matsuo, K., Baba, M., Fujii, W., & Palmer, J. B. (2007). Chewing and food consistency: effects on bolus transport and swallow initiation. *Dysphagia, 22*(2), 100-107. https://doi.org/10.1007/s00455-006-9060-5

Samant, S. S., Chapko, M. J., & Seo, H. S. (2017). Predicting consumer liking and preference based on emotional responses and sensory perception: A study with basic taste solutions. *Food Research International*, *100*(Pt 1), 325-334. https://doi.org/10.1016/j.foodres.2017.07.021

Samant, S. S., & Seo, H.-S. (2019). Using both emotional responses and sensory attribute intensities to predict consumer liking and preference toward vegetable juice products. *Food Quality and Preference*, *73*, 75-85. https://doi.org/https://doi.org/10.1016/j.foodqual.2018.12.006

Schifferstein, H. N. (2006). The perceived importance of sensory modalities in product usage: a study of self-reports. *Acta Psychologica*, *121*(1), 41-64. https://doi.org/10.1016/j.actpsy.2005.06.004

Schlich, P. (1996). Defining and validating assessor compromises about product distances and attribute correlations. In *Data handling in science and technology* (Vol. 16, pp. 259-306). Elsevier.

Sherman, P., & Deghaidy, F. S. (1978). Force-deformation conditions associated with the evaluation of brittleness and crispness in selected foods. *Journal of texture studies*, *9*(4), 437-459. https://doi.org/10.1111/j.1745-4603.1978.tb01217.x

Smith, C. H., Logemann, J. A., Burghardt, W. R., Zecker, S. G., & Rademaker, A. W. (2006). Oral and oropharyngeal perceptions of fluid viscosity across the age span. *Dysphagia*, *21*(4), 209-217. https://doi.org/10.1007/s00455-006-9045-4

Spence, C., Shankar, M., & Blumenthal, H. (2011). Sound bites': Auditory contributions to the perception and consumption of food and drink. *Art and the senses*, 207-238.

Spence, C., & Shankar, M. U. (2010). The influence of auditory cues on the perception of, and responses to, food and drink. *Journal of Sensory Studies*, *25*(3), 406-430. https://doi.org/10.1111/j.1745-459X.2009.00267.x

Spence, C., & Wang, Q. (2015). Sensory expectations elicited by the sounds of opening the packaging and pouring a beverage. *Flavour*, *4*(1), 35. https://doi.org/10.1186/s13411-015-0044-y

Szczesniak, A. S. (1988). The meaning of textural characteristics - crispness. *Journal of texture studies*, *19*(1), 51-59. https://doi.org/10.1111/j.1745-4603.1988.tb00924.x

Tanna, R. J., Lin, J. W., & De Jesus, O. (2022). Sensorineural hearing loss. In *StatPearls*. https://www.ncbi.nlm.nih.gov/books/NBK565860/

Varela, P., Chen, J., Fiszman, S., & Povey, M. J. W. (2006). Crispness assessment of roasted almonds by an integrated approach to texture description: texture, acoustics, sensory and structure. *Journal of Chemometrics*, *20*(6-7), 311-320. https://doi.org/10.1002/cem.1029

Velasco, C., Carvalho, F. R., Petit, O., & Nijholt, A. (2016). *A multisensory approach for the design of food and drink enhancing sonic systems* Proceedings of the 1st Workshop on

Multi-sensorial Approaches to Human-Food Interaction, Tokyo, Japan. https://doi.org/10.1145/3007577.3007578

Velasco, C., Jones, R., King, S., & Spence, C. (2013). The sound of temperature: what information do pouring sounds convey concerning the temperature of a beverage. *Journal of Sensory Studies, 28*(5), 335-345. https://doi.org/10.1111/joss.12052

Vickers, Z. M. (1982). Relationships of chewing sounds to judgments of crispness, crunchiness and hardness. *Journal of Food Science*, *47*(1), 121-124. https://doi.org/10.1111/j.1365-2621.1982.tb11041.x

Vickers, Z. M. (1984). Crispness and crunchiness - a difference in pitch? *Journal of texture studies*, *15*(2), 157-163. https://doi.org/10.1111/j.1745-4603.1984.tb00375.x

Wang, Q. J., & Spence, C. (2017). The role of pitch and tempo in sound-temperature crossmodal correspondences. *Multisensory Research*, *30*(3-5), 307-320. https://doi.org/10.1163/22134808-00002564

Williams, E. J. (1949). Experimental designs balanced for the estimation of residual effects of treatments. *Australian Journal of Chemistry, 2*(2), 149-168. https://doi.org/10.1071/CH9490149

Withers, C., Gosney, M. A., & Methven, L. (2013). Perception of thickness, mouth coating and mouth drying of dairy beverages by younger and older volunteers. *Journal of Sensory Studies, 28*(3), 230-237.

Worch, T., Lê, S., & Punter, P. (2010). How reliable are the consumers? Comparison of sensory profiles from consumers and experts. *Food Quality and Preference, 21*(3), 309-318. https://doi.org/10.1016/j.foodqual.2009.06.001

Youmans, S. R., & Stierwalt, J. A. (2011). Normal swallowing acoustics across age, gender, bolus viscosity, and bolus volume. *Dysphagia*, *26*(4), 374-384. https://doi.org/10.1007/s00455-010-9323-z

Zampini, M., & Spence, C. (2004). The role of auditory cues in modulating the perceived crispness and staleness of potato chips. *Journal of Sensory Studies*, *19*(5), 347-363. https://doi.org/10.1111/j.1745-459x.2004.080403.x

Chapter 4- Impacts of hearing loss on the perception and acceptance of aroma, flavor, and basic tastes

Abstract

Auditory cues can play a modulatory role in the perception of aroma, taste, and flavor. Thus, a deprivation of the sense of hearing could potentially have consequences on the multisensory perception of food. However, the assessment of the impact of hearing loss on the chemical senses is largely unexplored. This study was designed to evaluate the impacts of hearing loss on perception and liking of aromas, flavors, and tastes. More specifically, Universal Aromatic Scale (UAS) food samples and basic taste solutions with varying intensities of aromas, flavors, or tastes were evaluated by individuals with hearing loss (HL) and with normal hearing (NH). HL and NH individuals were asked to rate the aroma and flavor intensities, and acceptances of UAS foods. In addition, HL and NH individuals rated basic taste solutions with respect to sweetness, saltiness, sourness, bitterness, and umami intensities. Results showed that auditory loss impacted the flavor perception of UAS samples. A decrease in flavor perception was observed in the HL individuals compared to the NH group. In addition, aroma, or flavor liking of UAS samples were lower in the HL than those in the NH group. No impact of hearing loss was observed on the perception and overall enjoyment of sweet, salty, sour, bitter, and umami solutions. The outcomes of this study may shed some light on the development of sensory interventions designed to improve the food acceptance of communities with hearing loss.

Keywords: aroma, flavor, taste, hearing loss, auditory cues

1. Introduction

Hearing loss is one of the most common sensory disorders affecting 14.3% of the U.S. population aged 12 and over (Goman & Lin, 2016). Moreover, the percentage of people with hearing loss approximately doubles with every decade of life. As such, hearing loss is much more common among older adults and 91% of adults with hearing loss are aged 50 and older (Goman & Lin, 2016). As with many other sensory disorders, hearing loss, especially bilateral hearing loss, may have deep impacts on many aspects of a human well-being and quality of life (QoL) (Punch et al., 2019; Dalton et al., 2003; Rosenfeld & Goldsmith, 1997). Factors such as social isolation, the inability to participate in challenging listening situations, and the stress of dealing with the emotional reactions of those without a hearing loss, were noted to be highly associated with QoL in individuals with a hearing loss (Punch et al., 2019). In addition, people with hearing loss may give up their own personal interests and activities and this can impact on psychological wellbeing (Kvam et al., 2006). Poor communication plays a large part in increasing the risk of anxiety and depression in deaf and hard of hearing people (Ahmadi et al., 2017, Sinanović et al., 2004).

Food enjoyment is one aspect of QoL that is generally overlooked and has proven to be of great relevance on a person's wellbeing (Schlettwein-Gsell, 1992; Vailas & Nitzke, 1998). Schlettwein-Gsell (1992) stated that the ability to enjoy food is directly correlated to QoL and that food enjoyment becomes more important as age goes up. Food acceptability also promotes nutritional status and social behavior (Boesveldt & Parma, 2021). Indeed, eating is more than meal consumption, it can also be considered a social behavior e.g., enjoying family dinners, going out to a restaurant with friends, or cooking for your loved-ones (Boesveldt & Parma, 2021). Thus, a decrease in food enjoyment could worsened depressive symptoms and in turn impact QoL (Croy et al.,2014).

It is important to note that food perception is an intrinsically multisensory experience and not only gustatory, olfactory, and oral-somatosensory cues, but also visual, auditory, and trigeminal information play a significant role in modulating our perception of what we eat and drink (Carstens et al., 2002; Prescott & Stevenson, 1995; Zampini & Spence, 2010). The sense of hearing specifically has shown to modulate the way that we perceived flavor and taste. Most of the studies on this area, however, have focused on the effects of background noise, but not on the intrinsic sounds coming from the food itself. For example, Woods et al. (2011) found that the perceived intensity of gustatory cues (i.e., saltiness and sweetness) were diminished by loud background noise (75-85 dB) compared to quiet noise (45-44 dB). The latter authors did not find a corresponding effect of background noise on flavor ratings of the foods. In a separate study, Yan and Dando (2015) found that the effects of loud background noise were dependent on the taste quality. For example, Yan and Dando noticed that under loud background noise (80-85 dB) the perception of sweet taste was suppressed, umami taste was enhanced and the perception of the other three tastants was unaffected. Stafford et al. (2012) also found that participants perception of sweetness in alcoholic beverages was intensified while listening to loud background music than in its absence.

Even though that previous research established a relationship of background noise with flavors or tastes, there is a lack of definitive research on the interaction of sounds with the chemical senses. If such interaction exists, a primary step would be to evaluate the perceptions of aroma, flavor, and taste when the sense of hearing is in fact absent. Thus, this research was designed with the purpose of understanding the impacts of hearing loss on the perception and acceptance of aromas, flavors, and taste.

2. Materials and Methods

This study was conducted in conformance with the Declaration of Helsinki for studies on human subjects. The protocol used in this was approved by the Institutional Review Board of the University of Arkansas (Fayetteville, AR, USA). Written informed consent was obtained from each participant before participation.

2.1 Participants

The participants' demographic profiles are shown in Table 1. A total of 23 individuals with hearing loss (HL) (based on self-report diagnoses) [12 females and 11 males; mean age ± standard deviation (SD) = 62 ± 13.6 years old], and 23 individuals with normal hearing (NH) (12 females and 11 males; mean age ± SD = 61 ± 8.8 years old) were recruited via the consumer profile database of the University of Arkansas Sensory Science Center (Fayetteville, AR, USA), hearing clinics, deaf clubs, and the University of Arkansas campus. HL and NH groups did not significantly differ in terms of mean age ($P = 0.72$) and gender ratio ($P = 1.00$). Volunteers that reported having dentures, food allergies, other sensory deficiencies or cognitive impairments were not included in the study. About 56.5% of HL participants that participated in this study had been diagnosed with a sensorineural hearing loss, 82.6% of HL individuals had a moderate (41 to 55 dB HL) or higher degree of hearing loss and 69.6% of them indicated having a high-frequency hearing loss configuration. In addition, approximately 48% indicated wearing a hearing assistive device such as hearing aids. All NH individuals showed evidence of normal auditory status assessed via the adult hearing screening procedure recommended by the American Speech-Language-Hearing Association (ASHA, 2022) (refer to Chapter 3 for details on the hearing screening procedure).

2.2 Stimuli

Aroma and flavor samples

Five samples with varying aroma and flavor intensities were chosen for this study based on the Spectrum Universal Aromatic Scale (UAS) (Meilgaard et al., 2015): Nabisco Premium Original Saltine Crackers (Mondelez Global LLC, East Hanover, NJ, USA), Mott's Natural Applesauce (Mott's LLP, Plano, TX, USA), Minute Maid Frozen Orange Juice Concentrate (The Coca-Cola Co., Atlanta, GA), Welch's concord grape juice (Welch Foods, Concord, MA) and Big Red Gum (Wrigley Co., Chicago, IL). The UAS is a validated tool that employs a standardize scale ranging from 0 = none to 15 = very strong (Meilgaard et al., 2015). In aroma and flavor evaluation, the UAS is based on the philosophy that attribute intensities have been established on an absolute and universal basis. This is made by establishing the lowest and highest intensity point that could be perceived across products (Meilgaard et al., 2015; Muñoz & Civille, 1998). For example, the soda note in the Nabisco Premium Original Saltine Crackers is use as a reference point for the lowest intensity in aromatics with a score of 2.0 on a 15-point scale. Likewise, the cooked-apple note in Mott's Natural Applesauce has a score of 5.0; the orange note in Minute Maid Frozen Orange Juice Concentrate a score of 7.5, the grape note in Welch's concord grape juice (Welch Foods, Concord, MA) a score of 10.0 and the cinnamon note in Big Red Gum has the highest intensity on the 15-point scale with a score of 12.0.

Basic taste samples

The taste stimuli employed in this study were caffeine, citric acid, sodium chloride (NaCl), monosodium glutamate (MSG), and sucrose in water solutions corresponding to bitter, sour, salty, umami and sweet taste qualities, respectively (Table 2). The solutions were prepared according to the guidelines given for the Spectrum method (Meilgaard et al., 2015) and aimed to represent low (2.0 score on the Spectrum 15-point scale) and high (10.0 score on the Spectrum 15-point scale) concentrations for each tastant (Table 2).

2.3 Procedure

Prior to sample presentation, participants were shown written instructions about the experimental procedure. The evaluations were done in a quiet room to avoid the influence of external sounds on sample evaluation. HL individuals were instructed to remove their hearing aids, if wearing any. All participants experienced two experimental sessions, separated by one-day of each other. During the first session participants evaluated the aroma and flavor samples and during the second session participants assessed the basic taste solutions. For the aroma and flavor session, UAS samples were presented to the participants twice in two stages separated by a three-minute break. The first stage focused on the aroma and the second stage on flavor evaluation. During the aroma stage participants were instructed to smell the samples and were asked to not taste them. During the second stage the participants were asked to taste the samples. Samples in this session, for both aroma and flavor stages, were presented in order of lower to higher intensity. This was made in order to avoid carryover and sensory sensitivity and contrast effects.

During the basic taste session, tastants were presented in two stages separated by a three-minute break. The first stage focused on the evaluation of solutions with lower intensities and the second stage on the solutions with higher intensities. Basic taste qualities were randomized within each stage, except for bitter who was always presented last due to its strong after-taste sensation. Between sample presentations, a brief break was given for 60 s with unsalted crackers

(Nabisco Premium, Mondelēz Intl., East Hanover, NJ, USA) and spring water (Clear Mountain Spring Water, Taylor Distributing, Heber Springs, AR) for palate cleansing.

For the UAS samples participants were asked to rate the samples in terms of their perceived aroma and flavor intensity, on a 100-cm line scale ranging from 0 (not at all) to 100 (extremely intense). In addition, the aroma and flavor intensity of the UAS samples was also measured on a Just-About-Right (JAR) scale (1 = much too little, 4 = JAR, and 7 = much too much). For the basic taste solutions participants were asked to rate the samples in terms of their perceived taste (i.e., sweetness, bitterness, umami, sourness, or saltiness) intensity on a 100-cm line scale ranging from 0 (not at all) to 100 (extremely intense). Similarly, their perceived taste intensity was measured on a JAR scale (1 = much too little, 4 = JAR, and 7 = much too much). Overall liking of UAS samples and basic taste solutions were measured using traditional 9-point hedonic scales ranging from 1 (dislike extremely) to 9 (like extremely).

2.4 Statistical Analysis

Statistical analyses were performed using JMP® Pro (version 16.0, SAS Institute Inc., Cary, NS, USA) and XLSTAT software (Addinsoft, New York, NY, USA). To determine the effect of a hearing acuity on aroma, flavor and taste perceptions, and hedonic ratings, a three-way mixed model, treating “hearing group” and “food samples” as fixed effects and “participant” as a random effect, was employed. If a significant effect was identified, *post hoc* multiple pairwise comparisons between independent variables were conducted using Student *t*-tests. Stepwise multivariate regression analysis was performed to investigate the contribution of ratings of each sensory attribute on the overall acceptability of the samples and hearing groups. For the JAR scale data, a penalty analysis was used to identify how much each texture attribute affected the overall liking of cooked rice samples. JAR was determined when the percentage of the JAR score was greater than 70%, and no more than 20% of responses were on either minus (-) or plus (+) side of the scale (Choi et al., 2018). A statistically significant difference was defined as $P < 0.05$.

3. Results

3.1 Effects of hearing loss on perception and hedonic impression of food samples varying in aroma intensity

A three-way mixed model revealed no significant interactions between “hearing group” and “food sample” on ratings of aroma intensity ($P = 0.48$) or aroma liking ($P = 0.38$) (Supplementary Table 1). There was a significant main effect of “hearing group” on aroma liking ratings [$F(1, 44) = 5.80$, $P = 0.02$] (Figure 1). The HL group considered the aroma samples to be less acceptable compared to the NH group [$t(44) = -2.41$, $P = 0.02$]. No significant main effects of “hearing group” were found on ratings of aroma intensity ($P = 0.49$).

Penalty analysis results on the aroma JAR scores between the NH and HL groups are shown in Table 3. Overall, both hearing groups penalized the aroma intensity of the soda cracker or apple-sauce sample as being ‘not enough’ (Table 3). In addition, both groups considered the grape juice sample to be ‘just about right’ and the cinnamon gum to be ‘too much’ in terms of aroma intensity (Table 3). Approximately, 39.13% of HL individuals considered the aroma of the orange juice sample as ‘not enough’ significantly dropping the overall liking mean 2.23 points. Contrastingly, for the NH group the orange juice sample was considered ‘just about right’ (82.61%) in terms of aroma intensity.

3.2 Effects of hearing loss on flavor perception and hedonic impression of food samples with varying flavor intensities

A three-way mixed model revealed a significant interaction between ‘hearing group” and “food sample” on the flavor intensity [$F(4, 176) = 4.81$, $P = 0.001$] (Figure 2) and flavor liking [$F(4, 176) = 3.04$, $P = 0.02$] (Figure 3). *Post hoc t*-tests conducted to determine the source of interaction between hearing group and food samples on the flavor intensity ratings revealed that HL individuals rated the applesauce sample significantly less intense in flavor compared to the NH group [$t(44) = -2.01$, $P = 0.045$]. Similarly, HL individuals perceived the orange juice flavor as less intense compared to the NH counterparts [$t(44) = -3.13$, $P = 0.02$] (Figure 2). The same trend was observed across all the samples, but it was not statistically significant for the soda cracker ($P = 0.52$), grape juice ($P = 0.10$), and cinnamon gum ($P = 0.15$) samples (Figure 2). In terms of flavor liking, HL individuals liked the flavor of applesauce [$t(44) = -2.99$, $P = 0.003$] and the orange juice [$t(44) = -3.46$, $P = 0.001$] significantly less than their NH counterparts (Figure 3). Even though non statistically significant, HL individuals flavor liking scores for soda cracker ($P = 0.40$), grape juice ($P = 0.14$), and cinnamon gum ($P = 1.00$) were also lower than those of the NH group (Figure 3).

Table 4 shows the penalty analysis results on the flavor JAR scores between the NH and HL groups. Both hearing groups significantly penalized the flavor intensity of the soda cracker considering it as having ‘not enough’ flavor (Table 4). Approximately, 39.13% of the HL group regarded the flavor intensity of the applesauce sample as ‘not enough’ significantly dropping the overall liking mean 2.50 points. Contrastingly, for the NH group the applesauce sample was considered ‘just about right’ (82.61%) in terms of flavor intensity. In addition, 39.12% of the HL group rated the orange juice sample as ‘not enough’ in terms of flavor dropping 3.25 points of the overall liking. Contrastingly, 21.74% of NH individuals considered the orange juice sample as having ‘too much’ flavor intensity significantly dropping 2.20 points of the overall liking. The grape juice sample was significantly penalized by the NH group as having 'not enough' flavor, but this sample was considered to be 'just about right' for the HL group. Furthermore, 39.13% of NH individuals considered the cinnamon gum sample as having 'not enough' flavor causing a drop in the overall liking mean of 1.76. Conversely, 30.43% of HL individuals considered the cinnamon gum sample as having 'too much' flavor, further dropping 2.17 points of the overall liking.

3.3 Impacts of hearing loss on the perception and hedonic impression of basic taste solutions with varying intensities

A three-way mixed model revealed no significant interactions between "hearing group" and "tastant" on perceived sweetness ($P = 0.62$) (Figure 4a), saltiness ($P = 0.19$) (Figure 4b), sourness ($P = 0.98$) (Figure 4c), bitterness ($P = 0.17$) (Figure 4d), and umami ($P = 0.15$) (Figure 4e) intensity ratings . Similarly, no significant interactions between 'hearing group' and 'tastant' were found for the acceptance scores of sweetness ($P = 0.58$) (Figure 4a), saltiness ($P = 0.75$) (Figure 4b), sourness ($P = 0.78$) (Figure 4c), bitterness ($P = 0.32$) (Figure 4d), and umami ($P = 0.86$) (Figure 4e). In addition, no significant effects of 'hearing group' were found on the intensity ratings of sweetness ($P = 0.31$), saltiness ($P = 0.92$), sourness ($P = 0.46$), bitterness ($P = 0.43$), and umami ($P = 0.45$). No significant effects of 'hearing group' were also found on any of the liking scores of sweetness ($P = 0.74$), saltiness ($P = 0.07$), sourness ($P = 0.11$), bitterness ($P = 0.31$), and umami ($P = 0.14$). Overall, a significant effect of 'tastant' was found for sweetness [$F(1, 44) = 142.50$, $P < 0.001$], saltiness [$F(1, 44) = 136.42$, $P < 0.001$], sourness [$F(1, 44) = 99.18$, $P < 0.001$], bitterness [$F(1, 44) = 39.94$, $P < 0.001$], and umami [$F(1, 44) = 30.82$, $P < 0.001$] perceived intensity scores. Both groups were able to accurately discriminate the intensities of the basic taste solutions. Concretely, lower-intensity solutions were given lower perceived intensity scores and higher-intensity solutions higher perceived intensity scores by both hearing groups (Supplementary Table 2).

Penalty analysis results on the taste JAR scores between the NH and HL for low intensity solutions and high intensity solutions are shown in Tables 5 and 6, respectively. Overall, not many differences were observed between the two hearing groups in the penalization of solutions. Low intensity sweet, salty, sour and umami solutions were penalized by both groups for having 'not enough' intensity. Low intensity bitter and umami solutions were also considered as having 'too much' intensity by both groups (Table 5). For higher intensity solutions, sweet, salty, sour, bitter and umami solutions were largely penalized by both groups for having 'too much' taste intensity, significantly dropping the overall liking mean (Table 6).

4. Discussion

4.1 Impacts of a hearing loss on aroma and flavor perception and acceptance of UAS samples

This study focused on examining the relationships between hearing loss and the chemical senses. Overall, it was observed that a deficiency in auditory abilities stemming from a hearing loss impacted the perception of food flavors. While participants with hearing loss did not differ from individuals with normal hearing in terms of aroma intensity perception of food, their flavor intensity perception was significantly lower compared to the hearing controls. To the authors' best knowledge, this is the first study to focus on the differences in aroma and flavor perception between individuals with normal hearing and with hearing loss within a food matrix context. Previous research has mainly focused on the compensatory effects that a loss of hearing may have on olfactory sensitivity from a psychophysics angle. Overall, there have been conflict reports on smell sensitivity on deafness and there is still no conclusive evidence on the olfactory performance of deaf subjects compared to hearing controls. For example, Sorokowska et al. (2020) compared thresholds for detection of an unpleasant rotten food odor (fermented fish sauce) in deaf subjects and hearing controls. They did not observe any significant differences in smell sensitivity between the deaf groups and their matched controls. With a similar methodology, Guducu et al. (2016) assessed olfactory threshold, discrimination, identification, and total scores between deaf and control participants via the "Sniffin' Sticks" test. Guducu et al. found that discrimination and total scores of the deaf group were significantly lower than the control group. Similarly, Diekmann et al. (1994) used the Munich Olfaction test to show a diminished olfactory ability of individuals with hearing loss compared to hearing controls. It is important to note, that sample sizes of the latter mentioned studies were relatively small. Thus, generalized conclusions regarding olfactory sensitivity on individuals with hearing loss were prohibited.

The findings of this study support the notion that the depravation of one sense does not automatically imply an enhancement of other senses, as other authors have suggested (Bäckman, 1992; Singh et al., 2018; Lomber et al., 2010). For instance, Sharp et al. (2018) found that early auditory deprivation leads to improvement on the spatial mapping of touch. However, during tactile tasks there were no significant differences between hearing and deaf participants or hearing participants outperformed deaf individuals with respect to temporal aspects of tactile tasks (Bolognini et al., 2012; Papagno et al., 2016). Likewise, hearing loss does not influence reaction time to tactile stimuli (Heimler & Pavani, 2014) and does not alter tactile-motor synchronization in dance-like performance (Tranchant et al., 2017). Sensory deprived individuals, however, often self-assessed their sensory performance as more sensitive than healthy controls (Beaulieu-Lefebvr et al., 2011; Pieniak et al., 2022; Bolt, 2006). Deaf participants, specifically, rate their intact senses (i.e., vision, smell, taste, and touch) as more sensitive than hearing controls (Pieniak et al., 2020; Sorokowska et al., 2020). These positive self-evaluations made by deaf individuals might be an assertive self-presentation tactic used to manage impression made onto observers (Pieniak et al., 2020). The increased self-evaluation of sensory performance in the group of deaf participants seems to indicate that they share a widespread belief about sensory compensation. Accordingly, deaf people would incorporate such belief into their self-image what might lead to their higher self-ratings of sensory performance on the intact senses in comparison to their hearing counterparts (Pieniak et al., 2020).

One important finding of this study was that participants with hearing loss considered the aromas or flavors of the food stimuli as less acceptable than the hearing controls. These results might be explained by the relationships between intensity perception and hedonic impressions. Since individuals with hearing loss perceived the aroma and flavor of the samples to be less intense than individuals with normal hearing, this could have potentially contrasted with their already set expectations of the products, thus penalizing the samples on their acceptance scores (i.e., contrast effect) (Caporale et al., 2006; Cardello & Sawyer, 1992; Li et al., 2015). Another possible explanation lies in the multimodal aspect of food perception. As indicated in the introduction section, auditory cues have shown to play a role on flavor acceptance. Thus, a decrease in auditory feedback stemming from a hearing loss could have possible impacted the perception of other sensory attributes such as texture (see chapter 3), further modifying the perception of flavor. Previous work has shown that older consumers select samples by “thickness” and “firmness” as part of their liking decision, demonstrating the increased role of textural cues in food acceptance (Forde & Delahunty, 2002). In addition, flavor perception may cause the consumers focus to change in the direction of other product attributes (Szczesniak, 1990). Thus, the additive effect of a decreased textural perception and flavor perception could have impacted the overall acceptance of samples in the group with hearing loss.

4.2 Impacts of hearing loss on perception and hedonic impression of basic taste solutions

In this study, very little statistically significant effects of hearing groups were observed on perception and liking of gustatory cues. In addition, as shown in Figure 4, trends on the intensity perception of the various taste qualities between the groups were observed. More specifically, the group with hearing loss rated the solutions as less intense than the normal hearing individuals, especially the ones with lower concentrations. Figure 5 shows lower acceptance scores across all basic tastes (except for sweet taste) in the group with hearing loss, as well. Recently, Oleszkiewicz et al. (2023) reported similar trends in a study that aimed to determine gustatory sensitivity and taste liking in individuals with blindness or deafness. More specifically, using a taste spray test, Oleszkiewicz et al. found that individuals with hearing loss were consistently associated with a lower gustatory sensitivity (the difference was particularly salient for the bitter taste) and a decreased likability of taste (Oleszkiewicz et al., 2023), although the latter authors did not include umami on their study. These results might be explained by the hampering role that an impaired sense could have on the additional ‘intact’ senses. For example, visually impaired people, unlike sighted individuals, considered price and brand as the main drivers of their food purchasing decisions, whereas sensory aspects like taste and flavor were mentioned less frequently (Kostyra et al., 2017). Furthermore, the lack of auditory feedback in the group with hearing loss could have impacted the liking of the solutions as well. Indeed, previous research has shown a variety of crossmodal associations between taste and sound cues (Knöferle & Spence, 2012; Motoki et al., 2019). For instance, associations between high-pitched sounds and the names of various sour-tasting foods (such as lime, lemon juice, vinegar, and pickles), and between low-pitched sounds and foods having a bitter taste (such as coffee, beer, tonic water, and dark chocolate) have been demonstrated (Crisinel & Spence, 2009).

5. Conclusions

To summarize, this study showed that hearing loss reduced flavor perception and flavor acceptance of samples with mid to high flavor intensities in the UAS. More specifically the applesauce and orange juice samples of the UAS were perceived as less intense by the group with hearing loss compared to the group with normal hearing. In addition, apple sauce and orange juice were also liked less by individuals with hearing loss compared to hearing controls. Aroma acceptance of all UAS samples were also lower in the group with hearing loss compared to the group with normal hearing. Together these results highlight the hampering impact that sensory losses may have on the intact senses. In addition, the outcomes of this study may shed some light on the development of sensory interventions designed to improve the food acceptance of the community with hearing loss.

Table 1. Demographic profile of participants.

	Group with Normal Hearing		Group with Hearing Loss	
	N	**%**	***N***	**%**
Number of Participants	23		23	
Gender				
Men	11		11	
Women	12		12	
Mean Age (± Standard Deviation)	61.0 (± 8.8)		62.0 (± 13.6)	
Education Level[1]				
High school	3	13.04	3	13.04
Some college	1	4.35	5	21.74
2–4 year college degree	10	43.48	4	17.39
Master, or PhD degree	9	39.13	11	47.83
Annual Income (per year)				
<$20,000	0	0.00	2	8.70
$20,000 to $39,999	3	13.04	5	21.74
$40,000 to $59,999	4	17.39	3	13.04
$60,000 to $79,999	7	30.43	4	17.39
$80,000 to $99,999	8	34.78	5	21.74
>$100,000	1	4.35	4	17.39
Hearing Loss Type				
Conductive			8	34.78
Sensorineural			13	56.52
Mixed (conductive and sensorineural)			2	8.70
Other				
Hearing Loss Degree				
Mild			4	17.39
Moderate			8	34.78
Moderately Severe			6	26.09
Severe			2	8.70
Profound			3	13.04
Hearing Loss Configuration				
High Frequency			16	69.57
Middle Frequency			3	13.04
Low Frequency			4	17.39
Hearing Assistive Device Usage				
Hearing aids			11	47.83
Cochlear implants			1	4.35
Do not wear a HA device			10	43.48

Table 2. Concentrations of basic taste stimuli employed on this study.

Taste quality	Stimuli[1]	Low Intensity Solution Concentration (2.0 value on Spectrum™ Scale)	High Intensity Solution Concentration (10.0 value on Spectrum™ Scale)
Sweet	Sucrose	73.1 mM	292.1 mM
Salty	NaCl	34.2 mM	93.4 mM
Sour	Citric Acid	2.9 mM	7.8 mM
Bitter	Caffeine	2.8 mM	7.7 mM
Umami	MSG[2]	8.9 mM	41.3 mM

[1] Meilgaard, M., Civille, G.V. and Carr, B.T. 2015. Sensory Evaluation Techniques (5th Ed.). CRC Press, Boca Raton, Florida.
[2]Martin, C., Maire, A., Chabanet, C., and Issanchou, S. 2015. Equi-intensity across the Spectrum™ taste scales. Food Quality and Preference, 44, 25-83. doi:https://doi.org/10.1016/j.foodqual.2015.03.016

Table 3. Penalty analysis for each of the Universal Aromatic Scale (UAS) samples with respect to the aroma JAR scores evaluated by either individuals with normal hearing or with hearing loss.

	Sample	Level	Frequencies (%)	Mean Drops	Penalties	*P*-value
Group with Normal Hearing	Soda Cracker	not enough	65.22%	1.90		
		JAR	34.78%		1.9	<0.001
		too much	0.00%	0.00		
	Applesauce	not enough	52.17%	2.67		
		JAR	47.83%		2.67	<0.001
		too much	0.00%	0.00		
	Orange Juice	not enough	17.39%	1.93		
		JAR	82.61%			
		too much	0.00%	0.00		
	Grape Juice	not enough	13.04%	2.28		
		JAR	78.26%		1.744	<0.001
		too much	8.70%	0.94		
	Cinnamon Gum	not enough	8.70%	1.50		
		JAR	52.17%		1.727	0.001
		too much	39.13%	1.78		
Group with Hearing Loss	Soda Cracker	not enough	52.17%	0.92		
		JAR	47.83%		0.92	0.122
		too much	0.00%	0.00		
	Applesauce	not enough	34.78%	1.57		
		JAR	65.22%		1.57	0.005
		too much	0.00%	0.00		
	Orange Juice	not enough	39.13%	2.23		
		JAR	56.52%		2.33	<0.001
		too much	4.35%	3.23		
	Grape Juice	not enough	13.04%	1.21		
		JAR	82.61%			
		too much	4.35%	4.21		
	Cinnamon Gum	not enough	4.35%	3.00		
		JAR	60.87%		2.78	<0.001
		too much	34.78%	2.75		

Table 4. Penalty analysis for each of the the Universal Aromatic Scale (UAS) samples with respect to the flavor JAR scores evaluated by individuals with normal hearing or with hearing loss.

	Sample	Level	Frequencies (%)	Mean Drops	Penalties	*P*-value
Group with Normal Hearing	Soda Cracker	not enough	65.22%	1.95	1.91	0.01
		JAR	30.43%			
		too much	4.35%	1.29		
	Applesauce	not enough	13.04%	1.49		
		JAR	82.61%			
		too much	4.35%	2.16		
	Orange Juice	not enough	13.04%	0.67	1.63	0.003
		JAR	65.22%			
		too much	21.74%	2.20		
	Grape Juice	not enough	26.09%	0.59	0.82	0.004
		JAR	56.52%			
		too much	17.39%	1.17		
	Cinnamon Gum	not enough	39.13%	1.76	1.64	0.002
		JAR	56.52%			
		too much	4.35%	0.54		
Group with Hearing Loss	Soda Cracker	not enough	65.22%	1.63	1.63	0.008
		JAR	34.78%			
		too much	0.00%	0.00		
	Applesauce	not enough	39.13%	2.50	2.62	<0.001
		JAR	56.52%			
		too much	4.35%	3.62		
	Orange Juice	not enough	39.13%	3.25	2.95	<0.001
		JAR	47.83%			
		too much	13.04%	2.03		
	Grape Juice	not enough	17.39%	2.90		
		JAR	73.91%			
		too much	8.70%	3.15		
	Cinnamon Gum	not enough	17.39%	2.17	2.28	0.001
		JAR	52.17%			
		too much	30.43%	2.35		

Table 5. Penalty analysis table for basic taste solutions with low intensities (2.0 value on Spectrum™ Scale) evaluated by either individuals with normal hearing or with hearing loss.

	Variable	Level	Frequencies (%)	Mean Drops	Penalties	*P*-value
Group with Normal Hearing	Sweetness	not enough	52.17%	1.58	1.40	0.02
		JAR	34.78%			
		too sweet	13.04%	0.67		
	Saltiness	not enough	69.57%	1.19	1.30	0.07
		JAR	17.39%			
		too salty	13.04%	1.92		
	Sourness	not enough	60.87%	1.14	1.37	0.05
		JAR	17.39%			
		too sour	21.74%	2.00		
	Bitterness	not enough	26.09%	1.33	0.12	0.90
		JAR	13.04%			
		too bitter	60.87%	0.74		
	Umami	not enough	30.43%	1.35	1.56	0.04
		JAR	39.13%			
		too umami	30.43%	1.78		
Group with Hearing Loss	Sweetness	not enough	56.52%	0.35	1.03	0.21
		JAR	26.09%			
		too sweet	17.39%	3.25		
	Saltiness	not enough	52.17%	0.75	1.31	0.14
		JAR	8.70%			
		too salty	39.13%	2.06		
	Sourness	not enough	52.17%	0.00	0.81	0.50
		JAR	8.70%			
		too sour	39.13%	1.89		
	Bitterness	not enough	34.78%	0.04	1.42	0.11
		JAR	13.04%			
		too bitter	52.17%	2.33		
	Umami	not enough	21.74%	0.50	1.59	0.05
		JAR	43.48%			
		too umami	34.78%	2.90		

Table 6. Penalty analysis table for basic taste solutions with high intensities (10.0 value on Spectrum™ Scale) evaluated by either individuals with normal hearing or with hearing loss.

	Variable	Level	Frequencies (%)	Mean Drops	Penalties	*P*-value
Group with Normal Hearing	Sweetness	not enough	4.35%	2.00	3.18	0.003
		JAR	26.09%			
		too sweet	69.57%	3.25		
	Saltiness	not enough	0.00%	0.00	3.13	< 0.001
		JAR	26.09%			
		too salty	73.91%	3.13		
	Sourness	not enough	4.35%	0.63	1.51	0.08
		JAR	34.78%			
		too sour	60.87%	1.66		
	Bitterness	not enough	8.70%	0.00	1.47	0.11
		JAR	17.39%			
		too bitter	73.91%	1.65		
	Umami	not enough	17.39%	2.10	3.25	< 0.001
		JAR	43.48%			
		too umami	39.13%	3.77		
Group with Hearing Loss	Sweetness	not enough	8.70%	0.25	2.38	0.01
		JAR	34.78%			
		too sweet	56.52%	2.71		
	Saltiness	not enough	0.00%	0.00	2.78	0.01
		JAR	21.74%			
		too salty	78.26%	2.78		
	Sourness	not enough	8.70%	2.00	4.33	< 0.001
		JAR	21.74%			
		too sour	69.57%	4.63		
	Bitterness	not enough	4.35%	0.00	2.96	0.01
		JAR	4.35%			
		too bitter	91.30%	3.10		
	Umami	not enough	13.04%	2.50	3.81	< 0.001
		JAR	26.09%			
		too umami	60.87%	4.10		

Supplementary Table 1. Mean ratings (± standard deviation) of Universal Aromatic Scale (UAS) samples evaluated by either individuals with normal hearing or with hearing loss with respect to sensory perception and hedonic impression, and *P*-values associated with hearing group effect, food sample effect and hearing group and food sample interaction.

	Food Sample	Aroma Intensity[a]	Aroma Liking	Flavor Intensity	Flavor Liking
Group with Normal Hearing	Soda Cracker	24.90e (± 20.78)	6.26cd (± 1.36)	32.01d (± 18.90)	5.96def (± 1.72)
	Applesauce	43.74d (± 24.73)	6.61bc (± 1.56)	63.36ab (± 16.79)	7.87a (± 0.97)
	Orange Juice	61.91bc (± 20.77)	7.35ab (± 1.34)	69.64a (± 15.73)	7.43ab (± 1.34)
	Grape Juice	68.35b (± 18.98)	7.57a (± 1.04)	70.64a (± 17.28)	7.57ab (± 0.73)
	Cinnamon Gum	79.88a (± 16.62)	7.17ab (± 1.40)	57.94bc (± 22.63)	6.83bc (± 1.37)
Group with Hearing Loss	Soda Cracker	23.55e (± 14.92)	5.52d (± 1.41)	28.33d (± 16.46)	5.57f (± 1.47)
	Applesauce	45.30d (± 19.62)	6.52bc (± 1.34)	51.88c (± 22.35)	6.48cde (± 1.97)
	Orange Juice	52.72cd (± 24.15)	6.22cd (± 1.59)	51.74c (± 20.59)	5.83ef (± 1.99)
	Grape Juice	63.03b (± 14.77)	6.87abc (± 1.49)	61.20ab (± 18.69)	6.87bcd (± 1.87)
	Cinnamon Gum	80.17a (± 20.49)	6.91abc (± 2.00)	66.29ab (± 22.83)	6.83bcd (± 1.80)
Hearing Group Effect	*P*-value	0.49	0.02	0.10	0.01
Food Sample Effect	*P*-value	<0.001	<0.001	<0.001	<0.001
Hearing Group x Food Sample Interaction	*P*-value	0.48	0.38	0.001	0.02

[a] Mean ratings with different letters within a column represent a significant difference determined by Tukey's honestly significant difference (HSD) tests

Supplementary Table 2. Mean ratings (± standard deviation) of basic taste solutions evaluated by either individuals with normal hearing or with hearing loss with respect to perceived intensity, and *P*-values associated with hearing group effect, food sample effect and hearing group and food sample interaction.

		Sweetness[a]		**Saltiness**		**Sourness**		**Bitterness**		**Umami**	
	Tastant Intensity	**Intensity**	**Liking**	**Intensity**	**Liking**	**Intensity**	**Liking**	**Intensity**	**Liking**	**Intensity**	**Liking**
Group with Normal Hearing	Low	39.60b (± 20.86)	6.09 (± 1.38)	28.53b (± 24.48)	5.17a (± 1.30)	54.21b (± 33.33)	3.57 (± 1.44)	44.55b (± 22.14)	4.87a (± 1.29)	48.70bc (± 25.51)	4.83 (± 1.83)
	High	74.50a (± 17.73)	5.65 (± 2.42)	72.01a (± 19.21)	4.52ab (± 2.02)	76.76a (± 24.91)	2.78 (± 1.68)	72.91a (± 16.53)	4.39bc (± 1.99)	62.24a (± 23.52)	5.26 (± 2.38)
Group with Hearing Loss	Low	33.63b (± 27.86)	5.74 (± 1.71)	32.27b (± 27.78)	4.30ab (± 1.18)	41.65b (± 36.66)	3.43 (± 1.44)	39.39b (± 31.20)	4.26ab (± 1.57)	38.85c (± 25.52)	4.00 (± 1.93)
	High	70.15a (± 19.67)	5.70 (± 2.20)	66.94a (± 23.42)	3.83b (± 2.10)	76.86a (± 25.64)	2.17 (± 1.19)	67.93a (± 27.14)	3.61c (± 2.17)	61.94ab (± 25.86)	4.35 (± 2.42)
Hearing Group Effect	*P*-value	0.31	0.74	0.92	0.07	0.46	0.11	0.43	0.31	0.45	0.14
Food Sample Effect	*P*-value	<0.001	0.50	<0.001	0.04	<0.001	0.07	<0.001	<0.001	<0.001	0.12
Hearing Group x Food Sample Interaction	*P*-value	0.62	0.58	0.19	0.75	0.98	0.78	0.17	0.32	0.15	0.86

[a] Mean ratings with different letters within a column represent a significant difference determined by Tukey's honestly significant difference (HSD) tests.

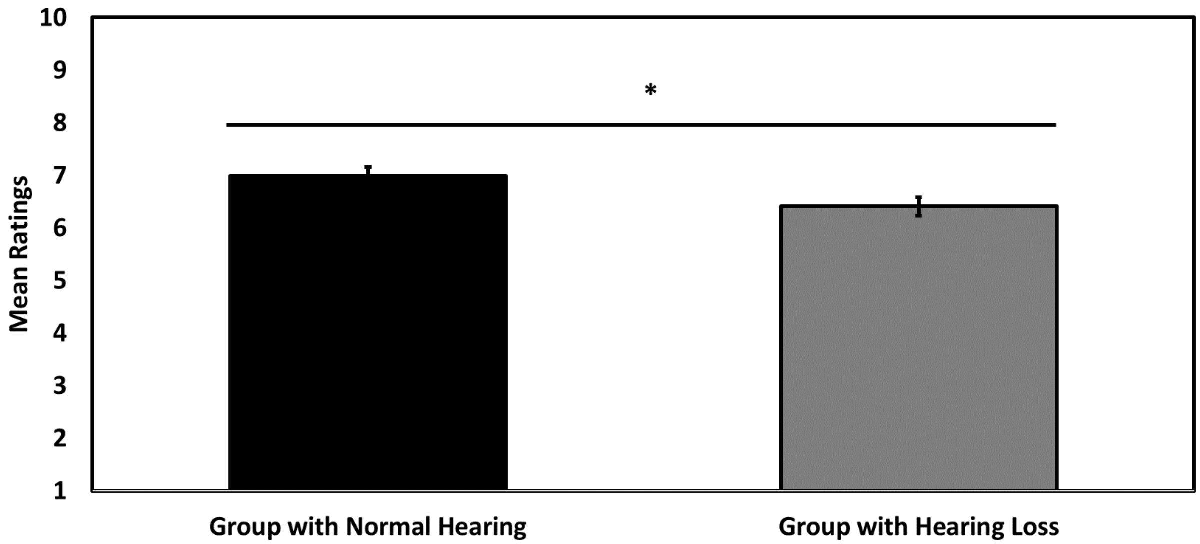

Figure 1. Aroma acceptance evaluations of Universal Aromatic Scale (UAS) samples by individuals with normal hearing and with hearing loss. Error bars represent standard errors of the means. *N.S.* represents no significant difference ($P > 0.05$).

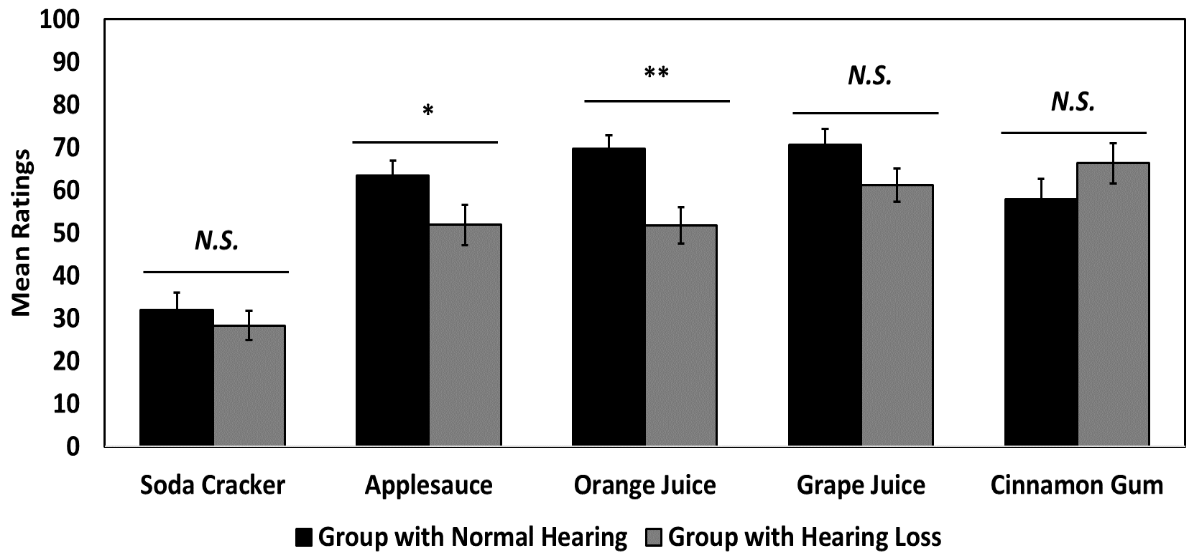

Figure 2. Flavor intensity evaluations of Universal Aromatic Scale (UAS) samples by individuals with normal hearing and with hearing loss. Error bars represent standard errors of the means. *N.S.* represents no significant difference ($P > 0.05$),* and ** represent a significant difference at $P < 0.05$ and $P < 0.01$, respectively.

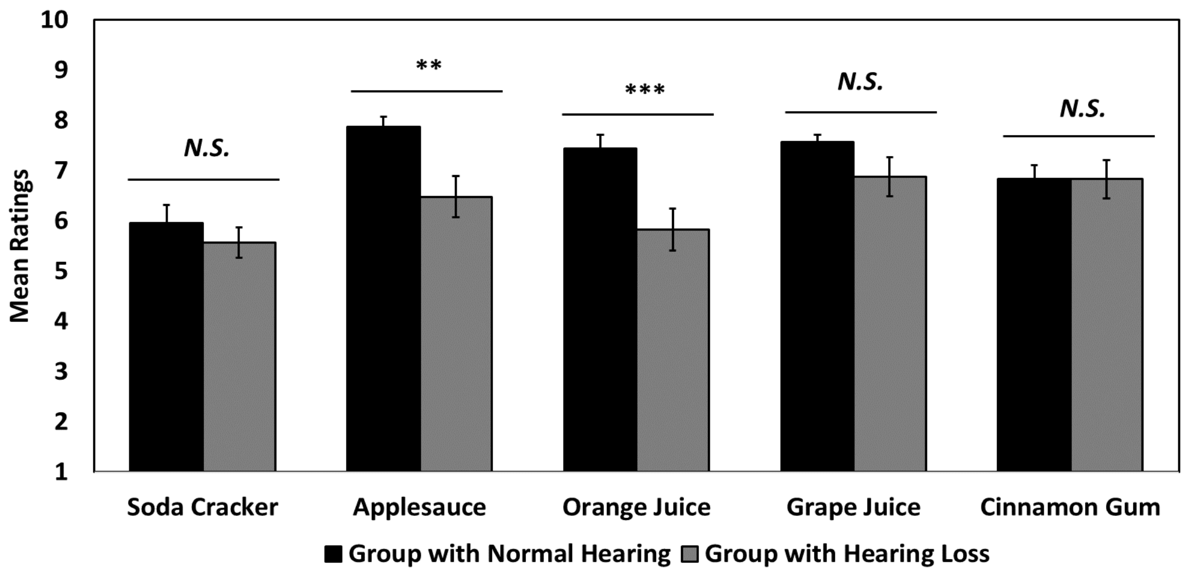

Figure 3. Flavor acceptance evaluations of Universal Aromatic Scale (UAS) samples by individuals with normal hearing and with hearing loss. Error bars represent standard errors of the means. *N.S.* represents no significant difference ($P > 0.05$),** and *** represent a significant difference at $P < 0.01$ and $P < 0.001$, respectively.

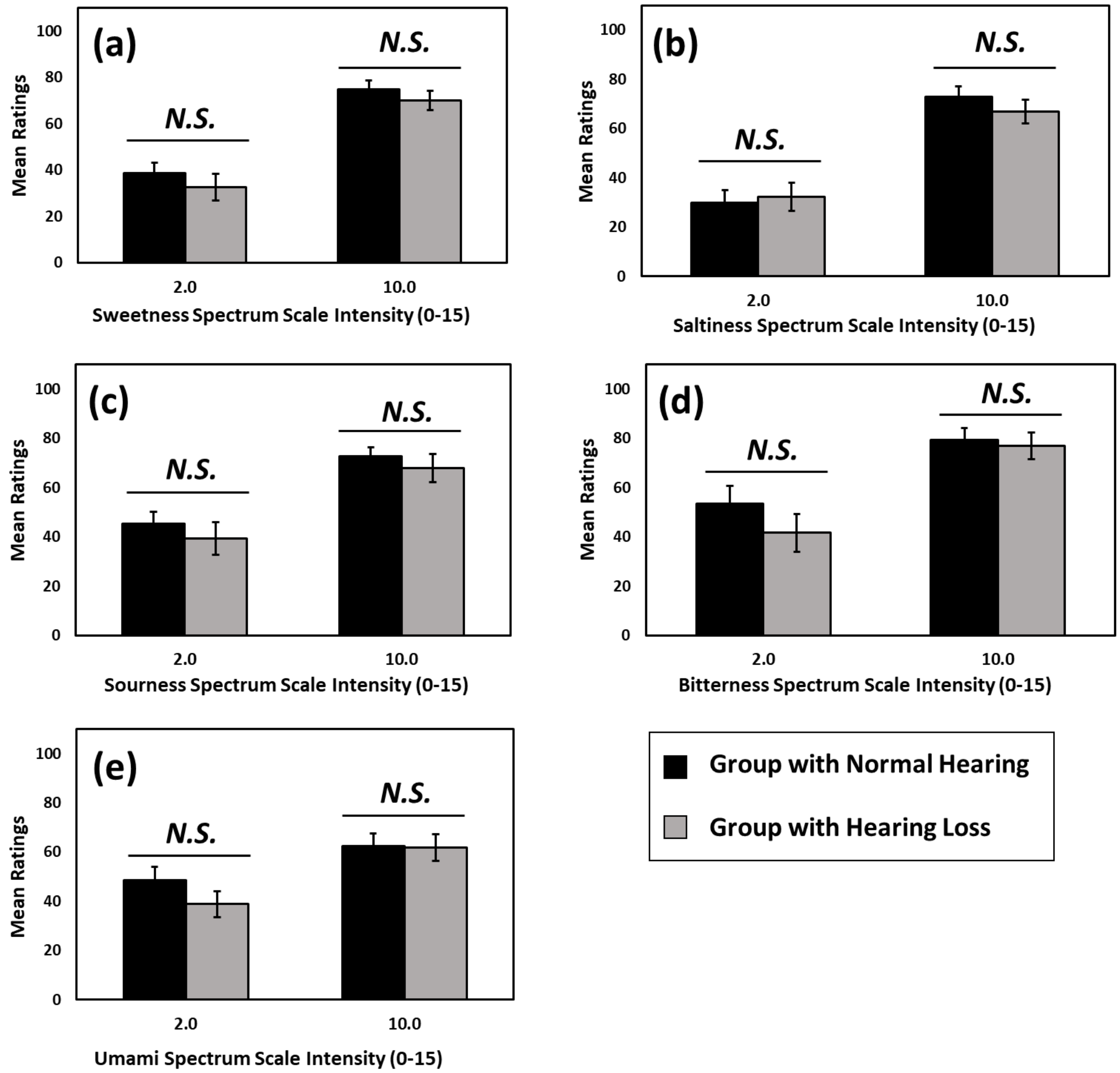

Figure 4. **Intensity evaluations of (a) sweet, (b) salty, (c) sour, (d) bitter and (e) umami taste solutions by individuals with normal hearing and with hearing loss.** Error bars represent standard errors of the means. *N.S.* represents no significant difference ($P > 0.05$).

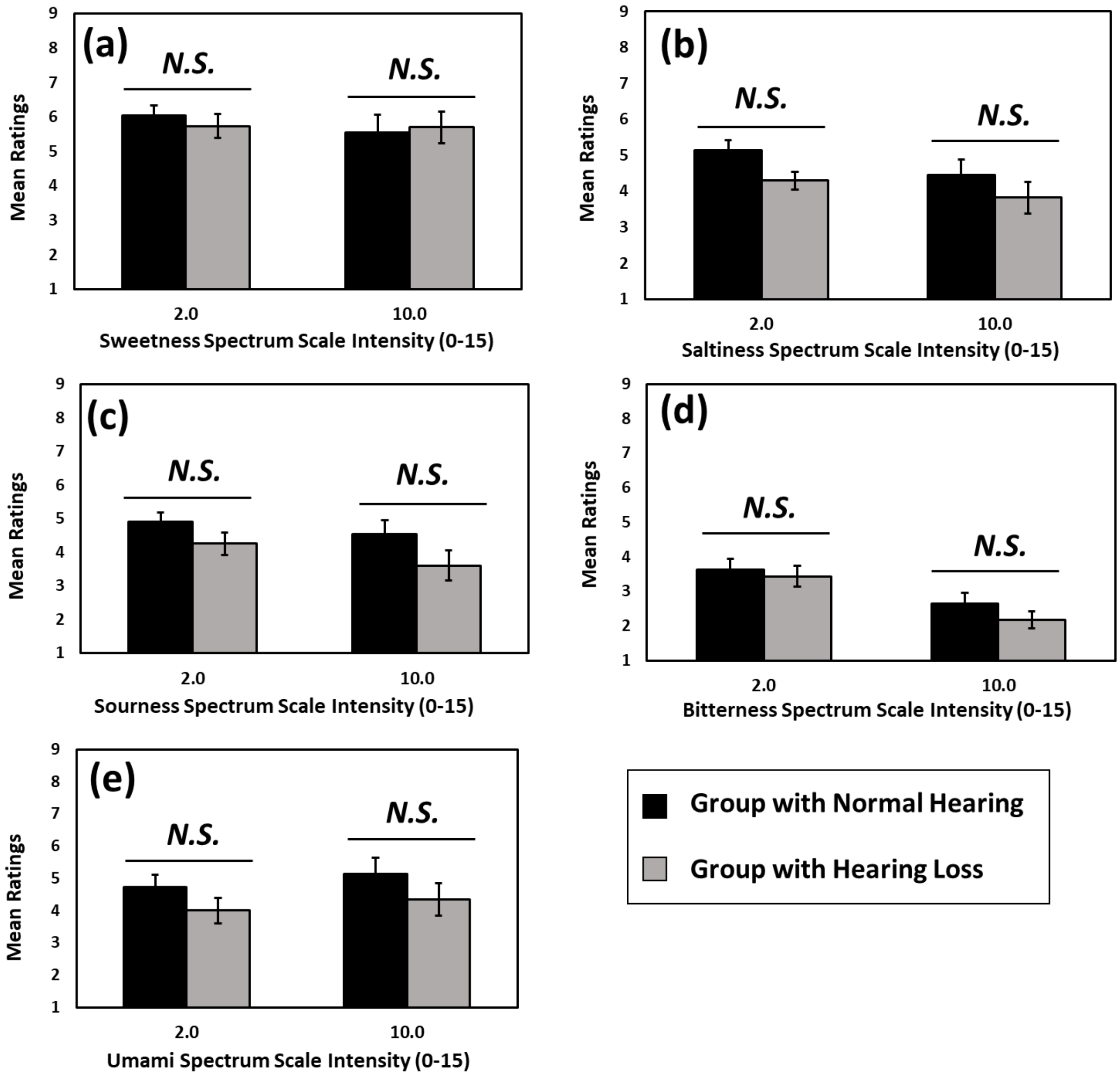

Figure 5. Acceptance ratings of (a) sweet, (b) salty, (c) sour, (d) bitter and (e) umami taste solutions by individuals with normal hearing and with hearing loss. Error bars represent standard errors of the means. *N.S.* represents no significant difference ($P > 0.05$).

References

Ahmadi, H., Daramadi, P. S., Asadi-Samani, M., Givtaj, H., & Sani, M. R. M. (2017). Effectiveness of Group Training of Assertiveness on Social Anxiety among Deaf and Hard of Hearing Adolescents. *Int Tinnitus J, 21*(1), 14-20. https://doi.org/10.5935/0946-5448.20170004

American Speech-Language-Hearing Association. (2022). *Adult Hearing Screening*. Rockville, MD : American Speech-Language-Hearing Association. www.asha.org/Practice-Portal/Professional-Issues/Adult-Hearing-Screening/.

Bäckman, L., & Dixon, R. A. (1992). Psychological compensation: a theoretical framework. *Psychol Bull, 112*(2), 259-283. https://doi.org/10.1037/0033-2909.112.2.259

Beaulieu-Lefebvre, M., Schneider, F. C., Kupers, R., & Ptito, M. (2011). Odor perception and odor awareness in congenital blindness. *Brain Res Bull, 84*(3), 206-209. https://doi.org/10.1016/j.brainresbull.2010.12.014

Boesveldt, S., & Parma, V. (2021). The importance of the olfactory system in human well-being, through nutrition and social behavior. *Cell and Tissue Research, 383*(1), 559-567. https://doi.org/10.1007/s00441-020-03367-7

Bolognini, N., Cecchetto, C., Geraci, C., Maravita, A., Pascual-Leone, A., & Papagno, C. (2012). Hearing Shapes Our Perception of Time: Temporal Discrimination of Tactile Stimuli in Deaf People. *Journal of Cognitive Neuroscience, 24*(2), 276-286. https://doi.org/10.1162/jocn_a_00135

Bolt, D. (2006). Beneficial blindness: Literary representation and the so-called positive stereotyping of people with impaired vision. *New Zealand Journal of Disability Studies, 12*, 80-100.

Caporale, G., Policastro, S., Carlucci, A., & Monteleone, E. (2006). Consumer expectations for sensory properties in virgin olive oils. *Food Quality and Preference, 17*(1), 116-125. https://doi.org/https://doi.org/10.1016/j.foodqual.2005.07.011

Cardello, A. V., & Sawyer, F. M. (1992). EFFECTS OF DISCONFIRMED CONSUMER EXPECTATIONS ON FOOD ACCEPTABILITY. *Journal of sensory studies, 7*(4), 253-277. https://doi.org/https://doi.org/10.1111/j.1745-459X.1992.tb00194.x

Carstens, E., Carstens, M. I., Dessirier, J.-M., O'Mahony, M., Simons, C. T., Sudo, M., & Sudo, S. (2002). It hurts so good: oral irritation by spices and carbonated drinks and the underlying neural mechanisms. *Food Quality and Preference, 13*(7-8), 431-443.

Choi, W. S., Jarma Arroyo, S. E., & Seo, H. S. (2018). Cross-cultural comparisons between Korean and US adults with respect to texture perception and acceptance of cooked milled rice. *International Journal of Food Science & Technology, 53*(9), 2181-2194.

Croy, I., Nordin, S., & Hummel, T. (2014). Olfactory Disorders and Quality of Life—An Updated Review. *Chemical Senses, 39*(3), 185-194. https://doi.org/10.1093/chemse/bjt072

Dalton, D. S., Cruickshanks, K. J., Klein, B. E., Klein, R., Wiley, T. L., & Nondahl, D. M. (2003). The impact of hearing loss on quality of life in older adults. *Gerontologist*, *43*(5), 661-668. https://doi.org/10.1093/geront/43.5.661

Diekmann, H., Walger, M., & von Wedel, H. (1994). Sense of smell in deaf and blind patients. *HNO, 42*(5), 264-269. http://europepmc.org/abstract/MED/8050914

Forde, C. G., & Delahunty, C. M. (2002). Examination of chemical irritation and textural influence on food preferences in two age cohorts using complex food systems. *Food Quality and Preference, 13*(7), 571-581. https://doi.org/https://doi.org/10.1016/S0950-3293(02)00036-8

Goman, A. M., & Lin, F. R. (2016). Prevalence of Hearing Loss by Severity in the United States. *Am J Public Health*, *106*(10), 1820-1822. https://doi.org/10.2105/AJPH.2016.303299

Guducu, C., Oniz, A., Ikiz, A. O., & Ozgoren, M. (2016). Chemosensory Function in Congenitally Blind or Deaf Teenagers. *Chemosensory Perception, 9*(1), 8-13. https://doi.org/10.1007/s12078-015-9199-2

Heimler, B., & Pavani, F. (2014). Response speed advantage for vision does not extend to touch in early deaf adults. *Experimental Brain Research, 232*(4), 1335-1341. https://doi.org/10.1007/s00221-014-3852-x

Knöferle, K., & Spence, C. (2012). Crossmodal correspondences between sounds and tastes. *Psychonomic Bulletin & Review*. https://doi.org/10.3758/s13423-012-0321-z

Kvam, M. H., Loeb, M., & Tambs, K. (2007). Mental health in deaf adults: symptoms of anxiety and depression among hearing and deaf individuals. *J Deaf Stud Deaf Educ, 12*(1), 1-7. https://doi.org/10.1093/deafed/enl015

Li, X. E., Jervis, S. M., & Drake, M. A. (2015). Examining Extrinsic Factors that Influence Product Acceptance: A Review. *Journal of Food Science*, *80*(5), R901-R909. https://doi.org/https://doi.org/10.1111/1750-3841.12852

Lomber, S. G., Meredith, M. A., & Kral, A. (2010). Cross-modal plasticity in specific auditory cortices underlies visual compensations in the deaf. *Nature Neuroscience, 13*(11), 1421-1427. https://doi.org/10.1038/nn.2653

Martin, C., Maire, A., Chabanet, C., & Issanchou, S. (2015). Equi-intensity across the Spectrum™ taste scales. *Food Quality and Preference, 44,* 75-83. https://doi.org/10.1016/j.foodqual.2015.03.016

Meilgaard, M., Civille, G. V., & Carr, B. T. (2015). *Sensory Evaluation Techniques* (5 ed.). CRC Press.

Motoki, K., Saito, T., Nouchi, R., Kawashima, R., & Sugiura, M. (2019). A Sweet Voice: The Influence of Cross-Modal Correspondences Between Taste and Vocal Pitch on Advertising Effectiveness. *Multisensory Research, 32*(4-5), 401-427. https://doi.org/https://doi.org/10.1163/22134808-20191365

Muñoz, A. M., & Civille, G. V. (1998). Universal, product and attribute specific scaling and the development of common lexicons in descriptive analysis. *Journal of sensory studies, 13*(1), 57-75.

Oleszkiewicz, A., Resler, K., Masala, C., Landis, B. N., Hummel, T., & Sorokowska, A. (2023). Alterations of gustatory sensitivity and taste liking in individuals with blindness or deafness. *Food Quality and Preference, 103*, 104712. https://doi.org/https://doi.org/10.1016/j.foodqual.2022.104712

Papagno, C., Cecchetto, C., Pisoni, A., & Bolognini, N. (2016). Deaf, blind or deaf-blind: Is touch enhanced? *Experimental Brain Research, 234*(2), 627-636. https://doi.org/10.1007/s00221-015-4488-1

Pieniak, M., Lachowicz-Tabaczek, K., Karwowski, M., & Oleszkiewicz, A. (2022). Sensory compensation beliefs among blind and sighted individuals. *Scandinavian Journal of Psychology, 63*(1), 72-82. https://doi.org/https://doi.org/10.1111/sjop.12781

Pieniak, M., Lachowicz-Tabaczek, K., Masalski, M., Hummel, T., & Oleszkiewicz, A. (2020). Self-rated sensory performance in profoundly deaf individuals. Do deaf people share the conviction about sensory compensation? *Journal of sensory studies, 35*(4), e12572. https://doi.org/https://doi.org/10.1111/joss.12572

Prescott, J., & Stevenson, R. J. (1995). Pungency in food perception and preference. *Food Reviews International, 11*(4), 665-698.

Punch, J. L., Hitt, R., & Smith, S. W. (2019). Hearing loss and quality of life. *J Commun Disord, 78*, 33-45. https://doi.org/10.1016/j.jcomdis.2019.01.001

Rosenfeld, R. M., Goldsmith, A. J., Tetlus, L., & Balzano, A. (1997). Quality of life for children with otitis media. *Arch Otolaryngol Head Neck Surg, 123*(10), 1049-1054. https://doi.org/10.1001/archotol.1997.01900100019002

Schlettwein-Gsell, D. (1992). Nutrition and the quality of life: a measure for the outcome of nutritional intervention.? *Am J Clin Nutr, 55*(6 Suppl), 1263S-1266S. https://doi.org/10.1093/ajcn/55.6.1263S

Sharp, A., Landry, S. P., Maheu, M., & Champoux, F. (2018). Deafness alters the spatial mapping of touch. *PLOS ONE, 13*(3), e0192993. https://doi.org/10.1371/journal.pone.0192993

Sinanovic, O., Brkic, F., Salihovic, N., Junuzovic, L., & Mrkonjic, Z. (2004). [Anxiety and depression in deaf and hard-of-hearing adults]. *Med Arh, 58*(2), 87-90. https://www.ncbi.nlm.nih.gov/pubmed/15202313 (Anksioznost i depresivnost kod odraslih tesko slusno ostecenih i gluhih osoba.)

Singh, A. K., Phillips, F., Merabet, L. B., & Sinha, P. (2018). Why Does the Cortex Reorganize after Sensory Loss? *Trends in Cognitive Sciences, 22*(7), 569-582. https://doi.org/https://doi.org/10.1016/j.tics.2018.04.004

Sorokowska, A., Hummel, T., & Oleszkiewicz, A. (2020). No Olfactory Compensation in Food-related Hazard Detection Among Blind and Deaf Adults: A Psychophysical Approach. *Neuroscience, 440*, 56-64. https://doi.org/https://doi.org/10.1016/j.neuroscience.2020.05.033

Stafford, L. D., Fernandes, M., & Agobiani, E. (2012). Effects of noise and distraction on alcohol perception. *Food Quality and Preference, 24*(1), 218-224. https://doi.org/https://doi.org/10.1016/j.foodqual.2011.10.012

Szczesniak, A. S. (1990). Texture: is it still an overlooked food attribute? texture has gained a new importance and desirability for today's consumer. *Food technology, 44*(9), 86-95.

Tranchant, P., Shiell, M. M., Giordano, M., Nadeau, A., Peretz, I., & Zatorre, R. J. (2017). Feeling the Beat: Bouncing Synchronization to Vibrotactile Music in Hearing and Early Deaf People. *Frontiers in Neuroscience, 11*. https://doi.org/10.3389/fnins.2017.00507

Vailas, L. I., & Nitzke, S. A. (1998). Food Enjoyment Scale for Older Adults. *Journal of Nutrition For the Elderly, 17*(3), 59-64. https://doi.org/10.1300/J052v17n03_04

Woods, A. T., Poliakoff, E., Lloyd, D. M., Kuenzel, J., Hodson, R., Gonda, H., Batchelor, J., Dijksterhuis, G. B., & Thomas, A. (2011). Effect of background noise on food perception. *Food Quality and Preference, 22*(1), 42-47. https://doi.org/https://doi.org/10.1016/j.foodqual.2010.07.003

Yan, K. S., & Dando, R. (2015). A crossmodal role for audition in taste perception. *J Exp Psychol Hum Percept Perform, 41*(3), 590-596. https://doi.org/10.1037/xhp0000044

Zampini, M., & Spence, C. (2010). Assessing the Role of Sound in the Perception of Food and Drink. *Chemosensory Perception, 3*(1), 57-67. https://doi.org/10.1007/s12078-010-9064-2

Chapter 5- Effects of hearing loss on environmental comfort, engagement, food perception, and food acceptance during social dining.

Abstract

Loud noises in restaurants are a major issue for the hard-of-hearing community dining food enjoyment. Some of the recent studies looking into the negative impacts of loud restaurant background noises on individuals with hearing loss (HL) dining enjoyment have been approached from a communication perspective. However, up to date, little focus has been paid on whether restaurant background noise could affect HL adults' dining enjoyment, environmental perceptions, and engagements in an ecologically valid context. This study aimed to determine HL individuals' levels of comfort, environmental perceptions, and engagement during social dining in an immersive restaurant context. This study also intended to validate the differences between HL and the group with normal hearing (NH) on food perception and acceptance in a realistic setting. Overall, HL individuals were less comfortable with the speech intelligibility and intensity of dining companions compared to their NH counterparts. Affective value and total engagement scores were also lower in the HL group compared to the NH group. Aspects such as having to raise their voices and speech intelligibility were mentioned by the HL group as reasons why they disliked the restaurant environment. Texture liking of garlic bread samples and flavor intensity scores of all food samples were also lower in the HL group compared to the NH group. This study reaffirmed the dampening impact that loud background noises often encountered in restaurants may have on individuals with a hearing loss. It also validates the impacts of hearing loss on food perception and acceptance in an ecologically valid context.

Keywords: hearing loss, social dining, environment, context, food perception, food acceptance

1. Introduction

Restaurants and cafés are no longer places where consumers go exclusively to eat food and drink beverages. These sites also add an important social component in most people's daily lives. However, loud background noises at restaurants can be particularly debilitating to the more than 460 million people worldwide affected by hearing loss. Although people with normal hearing do experience hearing difficulties in restaurants and other places of public accommodation, the inability to understand speech in a noisy restaurant can become so frustrating to individuals with hearing loss. Many of them tend to avoid outside dining and social activities (Lebo et al., 1994). Mosher and Jelonek (1991) used the 'Patient Satisfaction Survey' for adults with hearing loss to identify difficulty in listening environmental sounds. The results of that survey indicated that more than 80% of the group was dissatisfied with its ability to hear and understand conversations in restaurants, both with and without hearing aids. Under Title III of the American with Disabilities Act (ADA), restaurants and bars must accommodate individuals with disabilities (ADA, 2010). This implies that restaurants will need to reduce their ambient noise levels or implement architectural changes, such as ceiling panels, wall hangings, carpets, and/or drapery that can help control noise and reduce reverberation, for the hard-of-hearing consumer segment (Fink, 2017). However, since hearing loss is deemed as a "hidden" disability, restaurants often fail to accommodate this segment of consumers.

Some of the most recent studies looking into the effects of loud background noises at restaurants in individuals with hearing loss have been approached from a communication and speech discrimination perspective (Valente & Mispagel, 2008; Dawes et al., 2015). However, no studies have yet focused on whether restaurant background noise could affect adults with hearing loss food sensory perception and overall food enjoyment. In individuals with hearing loss extrinsic auditory cues, (i.e., sounds coming from other sources rather than the food itself), can significantly contribute to the perception of food and beverages (Spence et al., 2019). Additionally, due to the consistent rise in claims about noise levels in public places researchers have turn their attention into the impacts of high noise levels on food perception (Belluz, 2018; Moir, 2015; Spence, 2014a). Noise originating from various sources such as an airplane or the background of a restaurant or a bar has shown to modulate the perception of basic tastes (Rahne et al., 2018, Spence et al., 2014, Woods et al., 2011), odor (Rahne et al., 2018, Seo et al., 2012, Trautmann et al., 2017), flavor (Spence, 2014, Woods et al., 2011), and texture (Woods et al., 2011) attributes of food. It is still unclear why background noise acts as a suppressive of certain sensory attributes and as a booster of certain others. As an example of this, research conducted by Woods et al. (2011) found that the crispness intensity of a wide variety of foods was enhanced when subjects evaluated the food samples under a loud background noise (75-85 dB) as compared to a quiet background noise (45-55 dB). However, the opposite effect was found for sweet and saltiness intensities, where loud background noise seemed to act as a suppressor of these attributes (Woods et al., 2011). Additionally, Yan and Dando (2015) found that umami taste was enhanced under loud background noises (75-85 dB). The noise levels employed in the previously mentioned research are within the range of noise levels that are commonly found in restaurants. According to a study by Lebo et al. (1996), restaurants in the San Francisco bay area registered noise levels of up to 80 dBA or higher by the time the authors published their study. However, due to changes in regulations and differences that may be found in other areas of the countries more reports are needed regarding restaurant sound levels.

Most studies on the influence of extrinsic auditory cues have been conducted by employing traditional approaches, i.e., a single variable (e.g., sounds or noise levels) is manipulated in a laboratory setting and measurements of the impacts of this variable on food perception are registered (Sester et al., 2013). The underlying assumption of a traditional method is that everything that is found to be true in a laboratory setting can be translated elsewhere regardless of the context (Sester et al., 2013). Recent evidence has shown that the atmosphere in which food and drinks are tested and rated can significantly impact consumers' sensory perception and overall eating experience (Delarue et al., 2019; Sester et al., 2013; Wang & Spence, 2015; Sinesion et al., 2019; Stelick et al., 2018; Edwards et al., 2003). Several approaches to the study of eating behaviors within a context have been suggested in previous studies. One proposed alternative is to observe people in their natural eating or purchasing environments and measured the effects of a variable in this organic context. For example, real-setting studies have shown that playing background classical music (e.g., when compared to Top-40 hits) leads consumers to spend more on their food and beverage purchases, in a wine shop (Areni & Kim, 1993), a university cafeteria (North & Hargreaves, 1998; North et al., 2003, 2016), or even an African-themed restaurant (Wilson, 2003). However, as real situations are rich in details and vary on many dimensions at once, it is difficult to enumerate the different contextual variables (Meiselman et al., 2000) and measure their interactions by manipulating only the set of variables of interest. To avoid these problems previous researchers have suggested the use of immersive technologies that introduce people into a specific environmental condition while still having the control of a laboratory set-up. Sinesion et al. (2019) assessed the effectiveness of immersive technologies on simulating real-life environments by comparing the emotional profiling and liking values of four lager beer samples on five different test conditions (immersive room with a pub set-up, VR headset with the projection of the situation from a 360° Video, VR headset with the projection of the situation from 3D modeling and 360° photos, traditional in-lab testing environment, and in a real pub). They found that even though there was lesser product discrimination for hedonic questions and emotions assessments in the real pub and the immersive approaches as compared to the in-lab setting, all the immersive technologies tested improved consumers engagement, with a closer similarity of the results with the real pub obtained from the immersive room and VR 3D modeling (Sinesion et al., 2019). The aim of this study was to measure social dining comfort, environmental perceptions, and engagement of individuals with a hearing loss on a restaurant setting with levels of noise often found in restaurants. In addition, this study aimed to determine whether individuals with hearing loss and individuals with normal hearing could differ in food perception or acceptance under an immersive restaurant setting.

2. Materials and Methods

This study was conducted in conformance with the Declaration of Helsinki for studies on human subjects. The protocol used in this was approved by the Institutional Review Board of the University of Arkansas (Fayetteville, AR, USA). Written informed consent was obtained from each participant before participation.

2.1. Participants

The participants demographic profiles are shown in Table 1. Thirteen individuals with hearing loss (HL) (based on self-report diagnoses) [6 females and 7 males; mean age ± standard deviation (SD) = 62 ± 13 years old], and 13 individuals with normal hearing (NH) (8 females and 5 males; mean age ± SD = 63 ± 9 years old) were recruited via the consumer profile database of the University of Arkansas Sensory Science Center, hearing clinics, deaf clubs, and the University of Arkansas community. HL and NH groups did not significantly differ in terms of mean age (P = 0.87) and gender ratio (P = 0.69). Volunteers who reported having dentures, food allergies, other sensory deficiencies or cognitive impairments were not included in the study.

Eight (62%) HL participants had been diagnosed with a sensorineural hearing loss, eleven (84.7%) of HL individuals had a moderate (41 to 55 dB HL) or higher degree of hearing loss and eight (61.5%) of them indicated having a high-frequency hearing loss configuration. In addition, approximately seven (53.8%) indicated wearing a hearing assistive device such as hearing aids. All NH individuals showed evidence of normal auditory status assessed via the adult hearing screening procedure recommended by the American Speech-Language-Hearing Association (ASHA, 2022) (refer to Chapter 3 for details on the hearing screening procedure).

2.2. Food samples

Two food samples with varying intrinsic sound components were chosen for this study: garlic bread sticks (Great Value, Wal-Mart Stores, Inc. Bentonville, AR) and pita chips (Stacy's simply naked, Randolph, MA). These samples were chosen to mimic appetizers typically served in restaurants. Frozen garlic bread sticks were baked at 190°C for 10 min and served immediately after. Pita chips were served without any additional preparation.

Food samples were evaluated in terms of their texture and acoustic properties in order to quantify crispness and loudness intensities. More specifically, a TA-XT plus Texture Analyzer (Stable Micro Systems, Godalming, UK) was used for force/displacement measurements with a 50 kg load cell, using a spherical probe (P/36R); the samples were placed a Crisp Fracture Support Rig and corresponding platform. The test settings were set as follows: test speed 1 mm/s, trigger force 5 g, travel distance of the probe 3 mm. An Acoustic Envelope Detector (AED) was used for sound recording, with the corresponding software (Texture Exponent 32). The gain of the AED was set at one as suggested by Dias-Faceto et al. (2019). A Bruel and Kjaer free-field microphone (8-mm diameter), calibrated using an Acoustic Calibrator Type 4231 (94 dB and 114 dB SPL-1000 Hz) was positioned at 4 cm distance with an angle of 45° to the sample. Ambient acoustic and mechanical noise was filtered by the use of a high pass filter of 1 kHz. A low pass filter set the upper calibrated and measured frequency at 16 kHz. The data acquisition rate was 500 points per second for both force and acoustic signals. All tests were performed in a laboratory with no special soundproof facilities at room temperature. Five replications were performed for each sample. Force and sound pressure level (SPL) curves were simultaneously plotted. From the force curve the following parameters were extracted: peak force, area below the force curve, and gradient (slope of the curve up to the first major peak). From the sound curves, the number of sound peaks (drop in sound pressure level higher than 10dB), area under acoustic signal AED curve, and maximum sound pressure level (maximum of sound peaks) were obtained (Salvador et al., 2009). As shown in Supplementary Table 1, pita chips showed significantly higher values of peak force [$F(1, 8) = 47.24$, $P < 0.001$], area below the force curve [$F(1, 8) = 11.18$, $P = 0.01$], gradient [$F(1, 8) = 67.97$, $P < 0.001$], number of sound peaks [$F(1, 8) = 86.56$, $P < 0.001$], area under acoustic signal [$F(1, 8) = 16.85$, $P = 0.03$] and maximum sound pressure levels [$F(1, 8) = 12.53$, $P = 0.008$] compared to the garlic bread sample (Supplementary Table 1). According to Salvador et al. (2009), crispness is positively correlated to the number acoustic events, to the maximum sound pressure level and to the area below the acoustic and force curve, confirming that the pita chips sample was significantly crispier and louder compared to the garlic bread sample.

2.3. Immersive room environment and background noise specifications

The immersive room was designed by Igloo Vision Ltd.® (Craven Arms, Shropshire, UK). The total dimensions of the room are 3.38 m x 2.92 m x 2.74 m (L x W x H). The immersive video was projected onto 3 walls starting 35.56 cm up from the floor to 58.42 cm down from the ceiling, for a total projection area of approximately 17.5 m^2 over the 3 walls. The top and bottom borders, as well as the fourth wall where the door is located, are all painted black, while the projection surface was painted 'Mineral Haze 3' which is optimized for media projection. The immersive room was arranged to induce a restaurant context (Fig. 1).

Background noise was played utilizing a surround speaker system (JBL, Los Angeles, CA, USA). Media playback was handled by 'Igloo Vision's software' from a server in an adjoined room. The sounds were presented through the speaker system of the immersive room, and it consisted of typical background noises found in restaurants (a mixture of conversations, music, waiters, platter noises, etc.). The background noise level of the immersive room was measured via a sound level meter (R8080, REED Instruments, Wilmington, NC, USA) and it registered an integrated average value of 68.4 (dBA), a maximum of 76.4 dBA and a minimum of 60.7 dBA. The chosen noise intensity is typical of a restaurant ambient where levels vary from 60-80 dBA (Raab et al., 2013; Lebo at el., 1994). Sound level readings did not exceed 80 dBA, which is the level where hearing damage can begin to occur through sustained exposure (Raab et al., 2013).

2.4. Procedure

The day of the evaluation, four participants (two HL and two NH) were invited to participate in the test and asked to dine together to mimic a social dining experience. However, due to the uneven number of participants, for one of the seven sessions only two participants were present. In addition, a researcher pretending to be another participant, was asked to sit in with the participants during the experiment to ensure that participants were interacting with each other. Participants and the researcher were not familiar with each other. Before the test, HL individuals were instructed to remove their hearing aids, if wearing any. All sessions were run during lunch time and participants were asked to refrain from eating, drinking (except for drinking water), or cigarette smoking (Cho et al., 2017) for 2 hours prior to the participation.

Figure 2 shows a schematic chart flow of the experimental procedure. Participants were seated in the immersive restaurant table chairs. A menu, stainless steel cutlery, and a cup of water were placed on the table. Prior to sample presentation, the wait staff introduced the restaurant and welcomed the participants to drink some water (Clear Mountain Spring Water, Taylor Distributing, Heber Springs, AR, USA). The food samples were presented in a sequential monadic fashion and were randomized between each session to avoid any order bias. Between food sample presentations, a 10-min break was given to participants. This break had the purpose of simulating a restaurant typical wait period between an appetizer and the main dish. During this wait period, the researcher sitting with the participants modulated the conversation, allowing everyone to communicate and engage in the task.

Following each tasting, participants were asked to rate the appetizers in terms of flavor, bite sound, and texture intensity, on 9-point scales ranging from 1 (extremely weak) to 9 (extremely strong). In addition, flavor liking, texture liking, and overall liking of food samples were rated using traditional 9-point hedonic scales ranging from 1 (dislike extremely) to 9 (like extremely). At the end of the session, participants were asked to evaluate their environmental comfort and immersive engagement. More specifically, participants rated the overall environment liking on a 9-point hedonic scale ranging from 1 (dislike extremely) to 9 (like extremely). In addition, participants rated the ambient sound intensity, server's voice loudness, and companions, and server intelligibility (ability to understand or comprehend spoken words) on 9-point scales ranging from 1 (extremely weak) to 9 (extremely strong). Participants' comfort levels of the overall environment, sound levels, speech of companions, speech of server and chatting sound of other diners were measured on 9-point scales ranging from 1 (extremely uncomfortable) to 9 (extremely comfortable). Immersive engagement was measured via the 10-item engagement questionnaire (EQ) designed by Hannum and Simmons (2020). EQ is composed of 10 questions that measures three dimensions of engagement including active involvement, purposeful intent, and affective value. Higher scores in active involvement refers to highly engaged subjects that maintained their thoughts and focus directed on the task throughout the entirety of the sensory evaluation and do not get bored. The purposeful intent subscale assesses subjects' perceived personal relevance of the sensory evaluation to maintain their level of engagement. Engaged subjects are dedicated to finish the task. Finally, affective value addresses whether or not the sensory evaluation generated additional interest as it relates to a subject's feelings or attitude during the product testing. Highly engaged subjects were enjoying themselves and found the evaluation captivating, motivating them to provide additional effort during the task. Level of agreement for statements related to all three dimensions were collected using a 7-point category scale ranging from 1 (strongly disagree) to 7 (strongly agree). For each participant, all of their dimensional responses were combined linearly to derive a singular measure of engagement referred to as the total engagement score (TES). Participants were also encouraged to type what they liked or disliked about the environment in an open text format. All the responses were recorded using the sensory analysis software, Compusense Cloud® (Compusense Inc., Guelph, ON, Canada) via participants' personal smartphones.

2.5. Statistical Analysis

Statistical analyses were performed using JMP® Pro (version 16.0, SAS Institute Inc., Cary, NS, USA). To determine the effect of a hearing loss on environment comfort, liking, perception, and immersive engagement, a two-way mixed model, treating "hearing group" as a fixed effect and "participant" as a random effect, was employed. To determine the effect of a hearing loss on sensory perceptions and hedonic ratings, a three-way mixed model, treating "hearing group" and “food samples” as fixed effects and “participant” as a random effect, was employed. If a significant effect was identified, *post ho*c multiple pairwise comparisons using Student’s *t*-tests were conducted.

Free response data from the comments (what participants liked or disliked) were analyzed using text exploration and chi-square tests. Text exploration is a technique that allows processing and analyzing of semi-structured and unstructured textual data (Jarma Arroyo et al., 2020). Groups of words with similar roots or meaning (e.g., loudness and noise level) were clustered into a single term (e.g., noise level). A chi-square test was then conducted to determine whether the frequency of a specific term, reported as to what participants liked or disliked, differed between the two hearing groups. A statistically significant difference was defined as $P < 0.05$.

3. Results

3.1. Effects of hearing loss on environment liking, perception, and comfort and immersive engagement during social dining

A two-way mixed model revealed no significant effects of ‘hearing group’ on ratings of overall environment liking ($P = 0.58$), background sound intensity ($P = 0.51$), companions’ sound intensity ($P = 0.52$), wait staff’s sound intensity ($P = 0.46$), companions’ intelligibility ($P = 0.06$), wait staff’s intelligibility ($P = 0.10$), overall environment comfort ($P = 0.58$), background sound comfort ($P = 0.75$), wait staff’s sound comfort ($P = 0.14$), and chatting sound comfort of other diners ($P = 0.56$) (Table 2). The two-way mixed model revealed a significant main effect of ‘hearing group’ on companions’ sound comfort ratings [$F(1, 24) = 4.66$, $P = 0.04$] (Figure 3). HL individuals were significantly less comfortable with the sound intensity of their dining companions compared to the NH group. With regards to the engagement questionnaire a significant main effect of ‘hearing group’ was found on the affective value dimension of the EQ scale [$F(1, 24) = 18.71$, $P < 0.001$] (Figure 4). NH group's affective value was significantly higher than that of HL participants. Furthermore, a significant main effect of 'hearing group' was found on the total engagement scores [$F(1, 24) = 4.64$, $P = 0.04$] (Figure 4). More specifically, HL individuals, were less engaged in the sensory task compared to the NH group (Figure 4). No significant main effect of 'hearing group' were found on the EQ dimensions active involvement ($P = 0.07$) and purposeful intent ($P = 0.69$).

As shown in Table 3, there were no significant differences between the two hearing groups with respect to the frequency of specific positive terms (for all, $P > 0.05$), except for the enjoyment of meeting new people and dining companions [$\chi^2(3) = 0.38$, $P = 0.04$]. NH individuals mentioned that they enjoyed meeting new people or dining with new companions significantly more than their HL counterparts. There were no significant differences between the two hearing groups with respect to the frequency of specific negative terms directed toward the eating environment (for all, $P > 0.05$), except for comments regarding the fact that they have to raise their voice [$\chi^2(3) = 6.19$, $P = 0.01$] (Table 4). HL individuals mentioned that they did not like having to raise their voices due to the loud background significantly more often than NH controls.

3.2. Effects of hearing loss on food perception and acceptance during social dining

A three-way mixed model revealed no significant interactions between 'hearing group' and 'food sample' on ratings of overall liking ($P = 0.61$), flavor liking ($P = 0.57$), texture intensity ($P = 0.59$), and bite sound intensity ($P = 0.73$) except for texture liking [$F(1, 24) = 4.64$, $P = 0.04$] (Figure 5). Further *post hoc t*-tests revealed that HL individuals liked the texture of the garlic bread significantly less compared to NH individuals [$t(24) = -2.48$, $P = 0.02$]. However, no significant differences were observed between the two hearing groups with respect to the texture liking of pita chips ($P = 0.42$) (Figure 5). The three-way mixed model revealed a significant main effect of 'hearing group' on flavor intensity ratings [$F(1, 24) = 4.28$, $P = 0.049$] (Figure 6). HL individuals considered the samples to be significantly less intense in flavor compared to NH individuals. Furthermore, no significant main effects of 'hearing group' were found on ratings of overall liking ($P = 0.69$), flavor liking ($P = 0.67$), texture intensity ($P = 0.52$), and bite sound intensity ($P = 0.89$) (Table 5).

4. Discussion

As hypothesized, this study found that individuals with hearing loss social dining experience was significantly impacted by the noise levels in the immersive restaurant. More specifically, a reduced in comfort with the sound of dining companions' conversations was observed (Figure 3). This could have caused consumers with hearing loss to enjoy dining with new people significantly less than the NH group did (Table 3). Previous research has shown that adults with moderate-to-severe hearing loss understanding abilities and intelligibility are approximately 50% in the presence of minimal noise when a talker uses a normal voice range (60 dB) at one meters distance (Bottalico et al., 2022). Thus, any increment in background noise would have worsened individuals with hearing loss ability to comprehend spoken words. In addition, the impact of background noise would vary depending on degree of hearing loss. Bottalico and colleagues (2022) found that speech intelligibility significantly decreased for individuals with a mild hearing loss at a background noise level of 55 dB, for moderate-to-severe individuals with hearing loss at 50 dB and for subjects with normal hearing at 60 dB. In this study, 84.7% of individuals with hearing loss had a moderate or more severe degree of hearing loss, making speech intelligibility extremely challenging to them with the restaurant's background noise level. The effect of hearing assistive devices such as hearing aids or cochlear implants was not included in this study, however, the authors acknowledge that the use of hearing aids could have potentially impacted the observed results. In 2019, 7.1% of the U.S. adults used some form of hearing assistance (Madans et al., 2021), making it an important consideration to this research. Previous researchers have examined the benefits of hearing aids on aspects such as speech intelligibility in different real-world environments. Miles et al. (2022) found that benefits of non-linear hearing-aid amplification were highly dependent on the speech materials for a given background noise, degree of hearing loss, and environments. For example, there was no aided benefit in the office and church environment for listeners with mild hearing loss. This was because the unaided and aided scores were all at ceiling. Similarly, there was no aided benefit for the listeners with moderate and moderate-severe hearing loss in the food court environment (for either kind of speech material) because both sets of scores were near floor (Miles et al., 2022). Further studies should explore how different types of hearing assistive devices (cochlear implants, hearing aids, etc.) differ with respect to social dining enjoyment.

Contrary to hearing controls, participants with hearing loss mentioned that one of the aspects they disliked about the social dining environment was the fact that they felt they had to raise their voice to be able to communicate (Table 4). This phenomenon is described as the Lombard effect (Lombard, 1911); an involuntary tendency of the speaker to increase the vocal effort, while speaking in loud noise. Overall, a commonly observed slope for the Lombard effect is 0.3–0.6 dB in voice increase per dB in noise increase, when the noise exceeds 50 dB(A) (Lazarus, 1986; Bottalico et al., 2017). Bottalico and colleagues (2022) found that a significant change in the vocal effort was found at a noise level of 57-58 dB in older adults (representative of the current study sample). Older adults, especially ones with hearing losses, are impacted the most by vocal efforts required during dining in a loud space (Coelho et al., 2014). Age-related voice deterioration may begin around 60 years of age (Young & Mihailidis, 2010). For older adults naturally aged voice increases frequency of breathing which may lead to intra-word pauses. In addition, a decrease in muscle efficiency, an increase in tissue stiffness, a dry laryngeal mucosa, and slower cognitive function could affect vocal tract resonance, phonation, speech articulation; and rate of speech (Young & Mihailidis, 2010). These efforts could cause vocal fatigue in the older sector of the population, further decreasing their overall dining-out enjoyment as observed in this study. Indeed, older adults with hearing loss were found to be willing to spend less time and money in a restaurant with loud background noise levels (Bottalico et al., 2022).

Another important finding from this study was the lower affective values and engagement scores in the EQ task from individuals with hearing loss compared to individuals with normal hearing. By definition, affective value addresses whether or not the sensory evaluation generates additional interest and relates to a subject's feelings or attitude during the product testing (Hannum et al., 2020). This means that subjects with hearing loss were not as captivated by the task as individuals with normal hearing were. One reason for this could have been that the loud background noise provided a distracting environment to individuals with hearing loss further disengaging them from the sensory task. Immersive technologies have proven to provide ecological validity of sensory testing conditions in typical populations (i.e., normal hearing). However, this study provided empirical evidence that individual variations in engagement could exist across contextual environments. For participants with normal hearing, placing them in a full-context, could have allowed them to be more focused and actively involved in the task. For participants with hearing loss, however, a distracting environment with the presence of background noise/music may have affected participants' cognitive performance (Furnham & Strbac, 2002).

The outcomes of this chapter reinforced the results from the previous chapters regarding food perception and enjoyment of individuals with hearing loss and how these differ from those with a normal hearing. As demonstrated in Chapters 3 and 4, texture and flavor seem to be sensory attributes that were the most impacted by hearing loss. In particular, it was observed that individuals with hearing loss liked the texture of the food product with lower crispness (i.e., garlic bread) significantly less compared to individuals with normal hearing. Moreover, flavor intensity ratings were lower in the group with hearing loss compared to the group with normal hearing. This proves that the previously found results in Chapter 3 and 4 can still hold true under an immersive social dining compared to a laboratory setting. Previous research have found that the use of immersive technologies can increase the predictability and validity of liking and discrimination scores in sensory testing (Bangcuyo et al., 2015; Kong et al., 2020). Delarue et al. (2019) investigated the use of immersive scenarios on product discrimination and hedonic scores of non-alcoholic beverages. They found very little differences on the product discrimination and hedonic data collected in the lab and immersive conditions. Similarly, Hannum et al. (2019) after asking consumers to evaluate four wines in three environments- a traditional sensory booth, an immersive wine bar, and an actual wine bar, found that wine liking scores across environments were stable within the population supporting the findings of this dissertation.

This research findings could motivate restaurants and places of public accommodation to apply different strategies to reduce noise levels, improve speech intelligibility, and the Lombard effect not only to individuals with hearing loss but the hearing population as well. One particular manner that restaurants could aid hard-of-hearing patrons to enjoy their environment is by opting for a décor and/or a design that facilitates noise dampening such as carpeting, acoustic fabric-covered wall panels and sound-absorbing ceiling tiles. Indeed, there is an entire area of study in architecture specifically focused on the relationships between acoustics and architectural designs (Roy & Siebein, 2019). The architectural design (size, shape, and surfaces) of each building space determines the clarity of speech at any point within a room, and the absorbing materials used for décor will determine the loudness perception and intelligibility of speech (Brill et al., 2018). Furthermore, from a customer perspective there are different strategies that individuals with hearing loss could employ to avoid restaurants with poor acoustics. For example, to date various smartphone applications are currently available that provide restaurant noise levels in specific areas. Thus, users can sort and find restaurants that register lower decibel ratings that will allow higher speech intelligibility and an overall improvement in dining enjoyment.

5. Conclusions

The results of this chapter corroborate the deteriorating impact that restaurant noise levels have on the enjoyment of social dining for individuals with a hearing loss. We found that speech intelligibility of dining companions was decreased by loud noises in the background and the Lombard effect was more pronounced for subjects with hearing loss. This study also validated the previously found differences in food perception and acceptance between individuals with hearing losss and with normal hearing in a more ecological context. These results should motivate professionals at restaurants and places of public accommodation to apply different strategies to reduce noise levels and adjust to the ever-growing population with hearing loss. In addition, understanding the impact of context and external auditory cues on the perception of food could help guide sensory scientists and food developers to create food products with higher acceptability scores for the HL consumer segment.

Table 1. Demographic profile of participants.

	Group with Normal Hearing		Group with Hearing Loss	
	N	%	*N*	%
Number of Participants	13		13	
Gender				
Men	5	38.5	7	53.8
Women	8	61.5	6	46.2
Mean Age (± Standard Deviation)	63.1 (± 9.2)		62.4 (± 12.5)	
Education Level[1]				
High school	2	15.4	2	15.4
Some college	2	15.4	4	30.8
2–4 year college degree	5	38.5	3	23.1
Master, or PhD degree	4	30.8	4	30.8
Annual Income (per year)				
<$20,000	0	0.0	1	7.7
$20,000 to $39,999	1	7.7	3	23.1
$40,000 to $59,999	2	15.4	3	23.1
$60,000 to $79,999	7	53.8	1	7.7
$80,000 to $99,999	2	15.4	3	23.1
>$100,000	1	7.7	2	15.4
Hearing Loss Type				
Conductive			3	23.1
Sensorineural			8	61.5
Mixed (conductive and sensorineural)			2	15.4
Other				
Hearing Loss Degree				
Mild			2	15.4
Moderate			5	38.5
Moderately Severe			4	30.8
Severe			1	7.7
Profound			1	7.7
Hearing Loss Configuration				
High Frequency			8	61.5
Middle Frequency			2	15.4
Low Frequency			3	23.1
Hearing Assistive Device Usage				
Hearing aids			7	53.8
Cochlear implants			0	0.0
Do not wear a HA device			6	46.2

Table 2. Mean ratings (± standard deviation) of enviroment liking, perceptions and comfortability by either individuals with normal hearing or with hearing loss during social dining, and *P*-values associated with hearing group effect.

Environmental attribute	**Group with Normal Hearing**	**Group with Hearing Loss**	**Hearing Group Effect (*P*-value)**
Overall environment liking	5.77 (± 2.20)	5.31 (± 2.02)	0.58
Background sound intensity	7.77 (± 0.83)	7.46 (± 1.45)	0.51
Companions sound intensity	6.77 (± 1.09)	6.38 (± 1.80)	0.52
Wait staff sound intensity	6.00 (± 1.78)	5.46 (± 1.90)	0.46
Companions Intelligibility	7.31 (± 0.63)	6.08 (± 2.14)	0.06
Wait staff intelligibility	6.92 (± 1.66)	5.38 (± 2.75)	0.10
Overall environment comfort	5.62 (± 2.14)	5.15 (± 2.03)	0.58
Background sound comfort	3.69 (± 2.43)	4.00 (± 2.38)	0.75
Wait staff sound comfort	6.08 (± 2.10)	4.85 (± 2.03)	0.14
Chatting sound of other diners comfort	4.54 (± 2.33)	3.92 (± 2.90)	0.56

Table 3. A list of terms reported by at least 20% of participants and frequencies (*n*) with respect to what they liked of the eating environment for the two hearing groups.

Liked comments	**Group with Normal Hearing (*N* = 13)**	**Group with Hearing Loss (*N* = 13)**	**X^2 value (*P*-value)**
Meeting new people/ dining with new companions	11 (84.62%)	6 (46.15%)	4.25 (0.04)
Conversation quality	3 (23.08%)	4 (30.77%)	0.20 (0.66)
Ambience	5 (38.46%)	4 (30.77%)	0.17 (0.68)
Food	1 (7.69%)	4 (23.08%)	1.18 (0.28)

Table 4. A list of terms reported by at least 20% of participants and frequencies (*n*) with respect to what they disliked of the eating environment for the two hearing groups.

Disliked comments	**Group with Normal Hearing (*N* = 13)**	**Group with Hearing Loss Group (*N* = 13)**	**X^2 value (*P*-value)**
Noise level	11 (84.62%)	8 (61.54%)	1.76 (0.18)
Having to raise voice	0 (0.00%)	5 (38.46%)	6.19 (0.01)
Conversations intelligibility	1 (7.69%)	4 (30.77%)	2.23 (0.14)
Ambience	3 (23.08%)	2 (15.38%)	0.25 (0.62)

Table 5. Mean ratings (± standard deviation) of each food sample evaluated by either individuals with normal hearing or with hearing loss during social dining with respect to sensory perception and hedonic impression, and *P*-values associated with hearing group effect, food sample effect and hearing group and food sample interaction.

	Hearing Group	**Overall Liking**[a]	**Flavor Liking**	**Texture Intensity**	**Bite Sound Intensity**
Garlic Bread	Group with Normal Hearing	8.31a (± 0.95)	8.38a (± 0.65)	6.31a (± 0.95)	4.23a (± 1.79)
	Group with Hearing Loss	8.00a (± 0.91)	8.08a (± 0.86)	6.23a (± 1.17)	4.00a (± 2.16)
Pita Chips	Group with Normal Hearing	7.08a (± 1.44)	7.15a (± 1.41)	7.77a (± 1.88)	7.46a (± 1.94)
	Group with Hearing Loss	7.08a (± 1.50)	7.15a (± 1.46)	7.31a (± 1.38)	7.54a (± 0.88)
Hearing Group Effect	*P*-value	0.69	0.67	0.52	0.89
Food Sample Effect	*P*-value	0.001	0.001	0.001	<0.001
Hearing Group x Food Sample Interaction	*P*-value	0.61	0.57	0.59	0.73

[a] Within a cell, mean ratings with different letters within a column represent a significant difference determined by Student *t* tests.

Supplementary Table 1. Mechanical and acoustical properties of samples chosen for this study.

	Garlic Bread	Pita Chips	Food Sample Effect (*P*-value)
Mechanical features of texture			
Peak force (g)	80.52b (± 42.99)	2188.63a (± 684.46)	<0.001
Area under force-deformation curve (g/sec)	118.87b (± 64.19)	320.61a (± 118.68)	0.01
Gradient (g/sec)	30.40b (± 16.92)	6558.00a (± 1770.33)	<0.001
Acoustic features of texture			
Number of sound peaks AED	46.20b (± 9.12)	87.60a (± 3.97)	<0.001
Area under deformation-acoustic signal AED curve (dB/sec)	266.02b (± 23.21)	340.82a (± 33.48)	0.003
Maximum of sound peaks AED (dB)	79.55b (± 6.04)	89.41a (± 1.52)	0.008

[a] Mean ratings with different letters within a row represent a significant difference determined by Student *t* tests.

Figure 1. Example of the immersive room restaurant setting and the diners interacting (Source: photo by author).

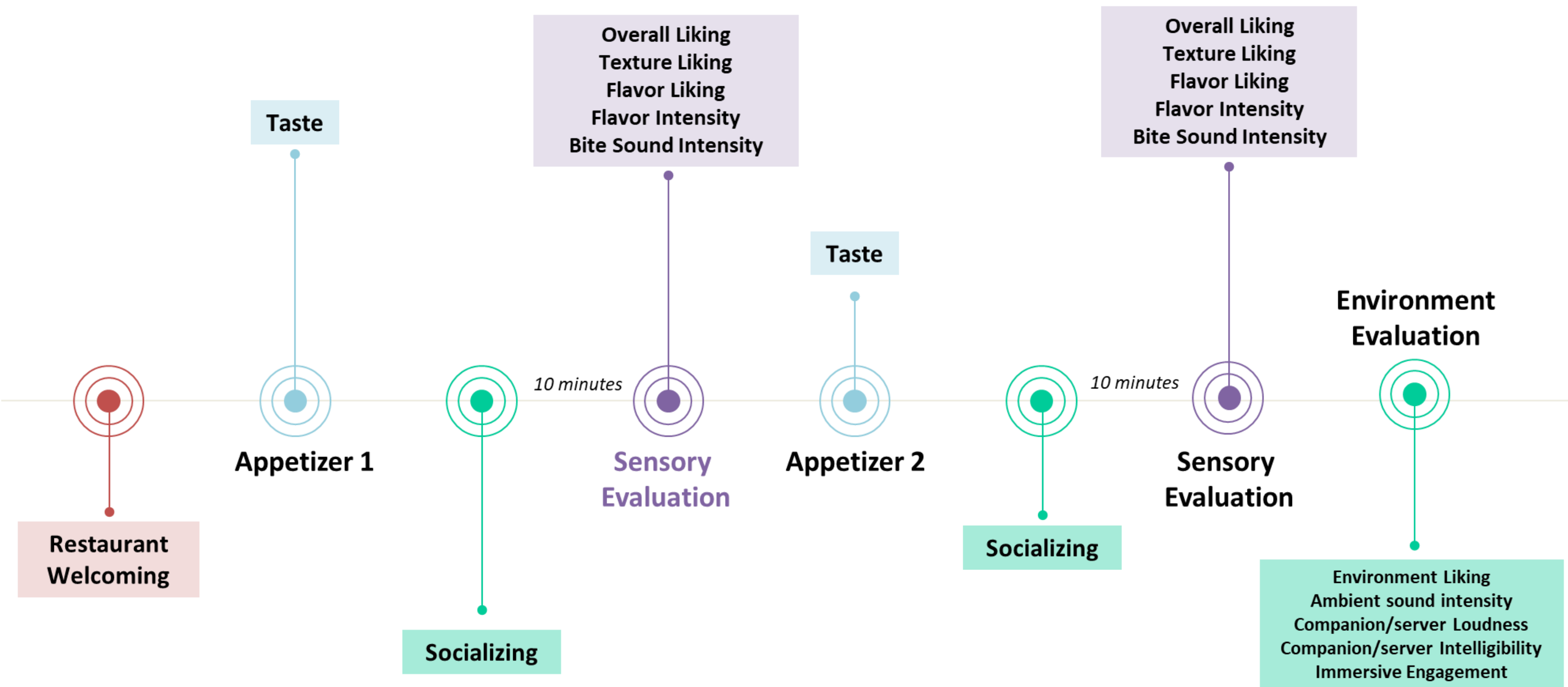

Figure 2. Schematic chart flow of the experimental procedure.

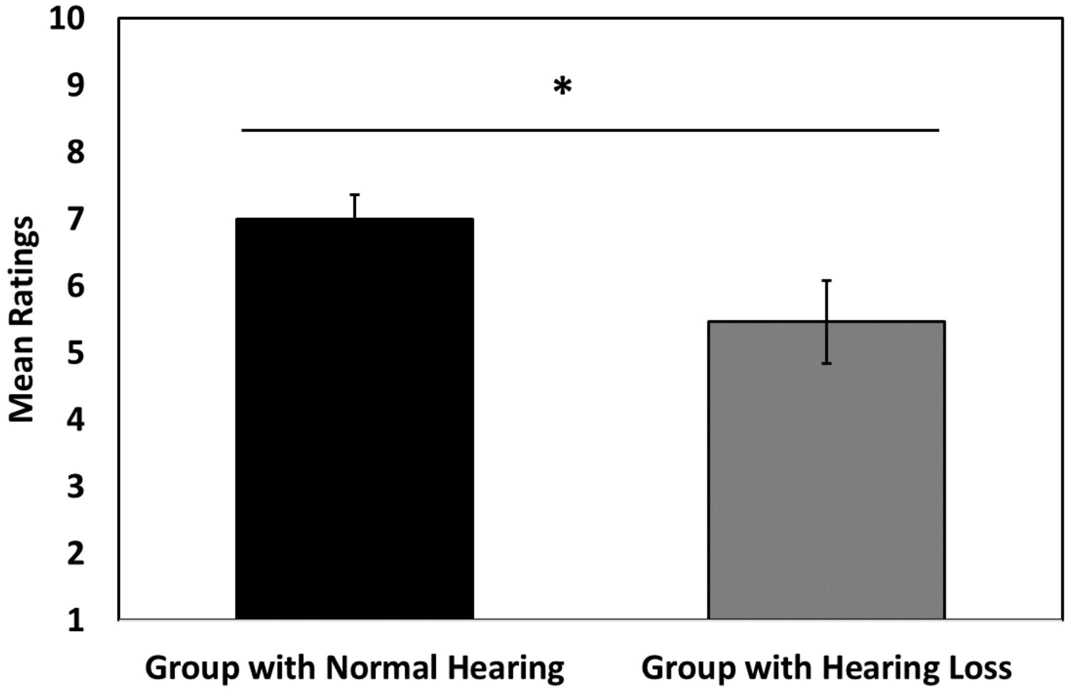

Figure 3. Effect of 'hearing group' on companions sound comfortability ratings. Error bars represent standard error of the means. *, indicates significant differences at $P < 0.05$.

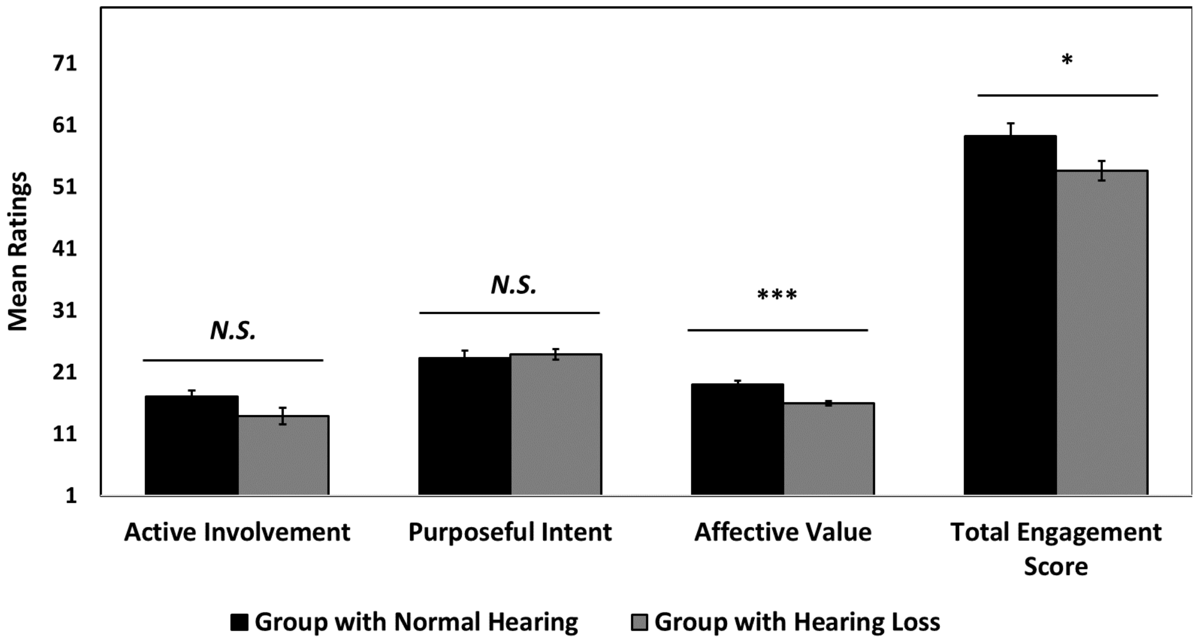

Figure 4. Effect of 'hearing group' on active involvement, purposeful intent, affective value and total immersive engagement (EQ) scores. Error bars represent standard error of the means. *N.S.* denotates no significant difference ($P > 0.05$). *,*** indicates significant differences at $P < 0.05$ and $P < 0.001$, respectively.

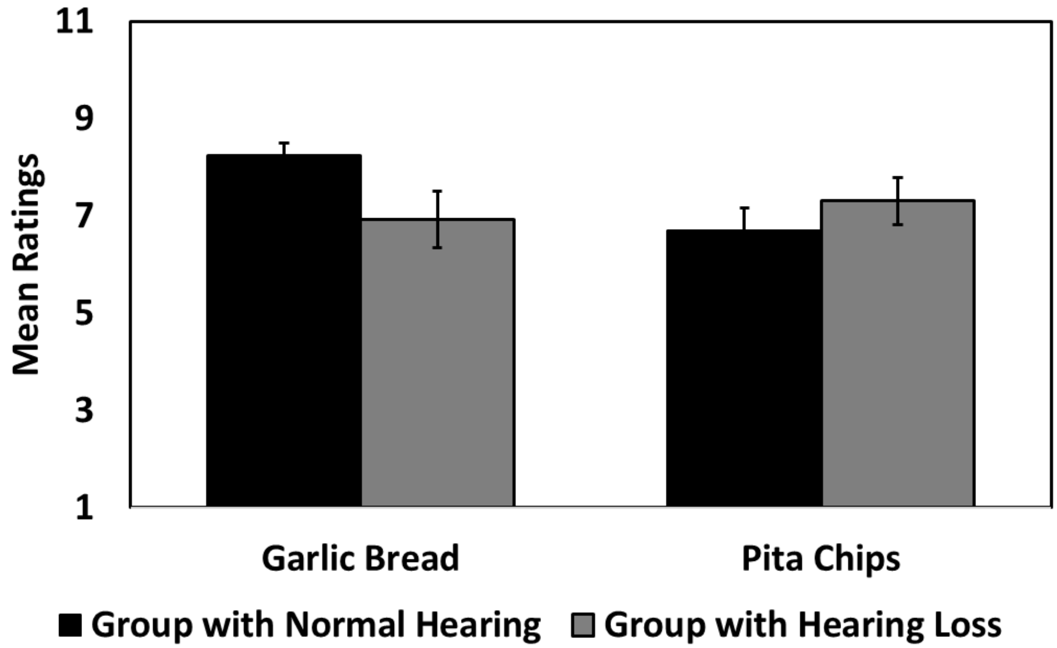

Figure 5. Interaction between 'hearing group' and 'food sample' with respect to texture liking. Error bars represent standard error of the means. *N.S.* indicates no significant difference ($P > 0.05$). *, indicates significant differences at $P < 0.05$.

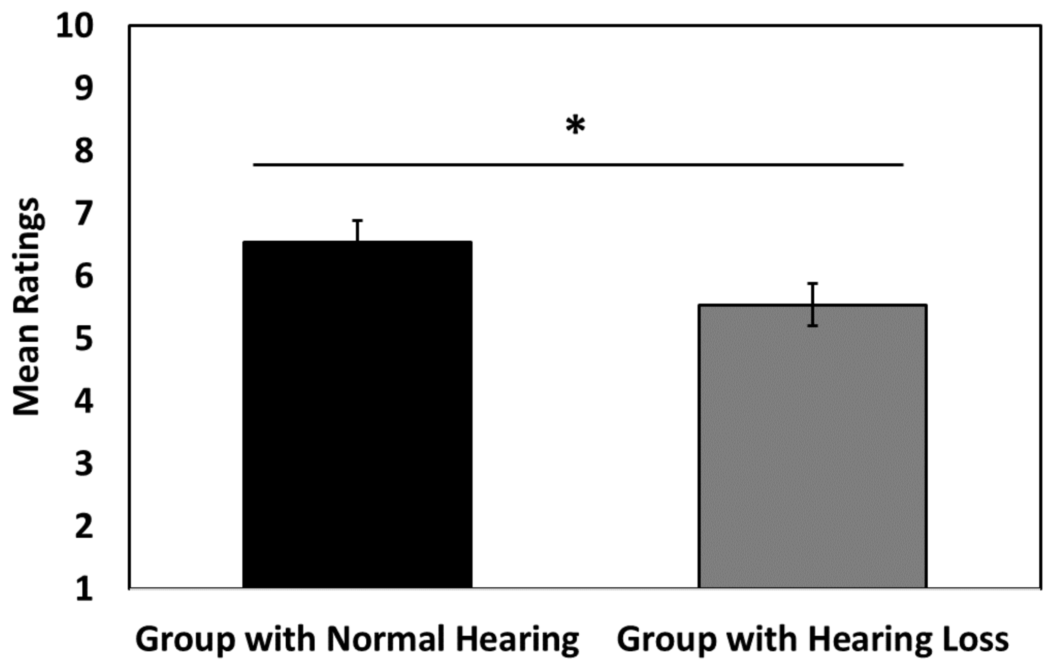

Figure 6. Main effect of 'hearing group' on flavor intensity ratings of the two food samples evaluated in this study. Error bars represent standard error of the means. *, indicates significant differences at $P < 0.05$.

References

American with Disabilities Act of 1990, 42 U.S.C § 12101 (2010). https://www.ada.gov/regs2010/titleIII_2010/titleIII_2010_regulations.pdf.

Areni, C. S., & Kim, D. (1993). The influence of background music on shopping behavior: classical versus top-forty music in a wine store. *Advanced Consumer Research, 20*, 336-340. https://www.acrwebsite.org/volumes/7467/volumes/v20/NA-20

Bangcuyo, R. G., Smith, K. J., Zumach, J. L., Pierce, A. M., Guttman, G. A., & Simons, C. T. (2015). The use of immersive technologies to improve consumer testing: The role of ecological validity, context and engagement in evaluating coffee. *Food Quality and Preference, 41*, 84-95. https://doi.org/https://doi.org/10.1016/j.foodqual.2014.11.017

Belluz, J. (2018). *Why restaurants became so loud — and how to fight back. "I can't hear you.* Retrieved December 14, 2022 from https://www.vox.com/2018/4/18/17168504/restaurants-noise-levelsloud-decibels

Bottalico, P., Passione, II, Graetzer, S., & Hunter, E. J. (2017). Evaluation of the starting point of the Lombard Effect. *Acta Acustica united with Acustica, 103*(1), 169-172. https://doi.org/10.3813/AAA.919043

Bottalico, P., Piper, R. N., & Legner, B. (2022). Lombard effect, intelligibility, ambient noise, and willingness to spend time and money in a restaurant amongst older adults. *Scientific Reports- Nature, 12*(1), 6549. https://doi.org/10.1038/s41598-022-10414-6.

Brill, L. C., Smith, K., & Wang, L. M. (2018). Building a sound future for students: Considering the acoustics of occupied active classrooms. *Acoustics Today, 14*(3), 14-22. https://acousticstoday.org/building-sound-future-students-considering-acoustics-occupied-active-classrooms-laura-c-brill/

Coelho, A. C., Medved, D. M., & Brasolotto, A. G. (2015). Hearing loss and the voice. In B. Fayez, Jr. (Ed.), *Update On Hearing Loss* (pp. Ch. 6). IntechOpen. https://doi.org/10.5772/61217

Cho, S., Camacho, A., Patten, E., Costa, D., Damiao, B. S., Fuller, R., da Palma, L., & Seo, H.-S. (2017). The effect of cigarette smoking on chemosensory perception of common beverages. *Chemosensory Perception, 10*(1), 1-7. https://doi.org/10.1007/s12078-016-9219-x

Dawes, P., Emsley, R., Cruickshanks, K. J., Moore, D. R., Fortnum, H., Edmondson-Jones, M., McCormack, A., & Munro, K. J. (2015). Hearing loss and cognition: the role of hearing AIDS, social isolation and depression. *PLoS One, 10*(3), e0119616. https://doi.org/10.1371/journal.pone.0119616

Delarue, J., Brasset, A. C., Jarrot, F., & Abiven, F. (2019). Taking control of product testing context thanks to a multi-sensory immersive room. A case study on alcohol-free beer. *Food Quality and Preference, 75*, 78-86. https://doi.org/10.1016/j.foodqual.2019.02.012

Dias-Faceto, L. S., Salvador, A., & Conti-Silva, A. C. (2020). Acoustic settings combination as a sensory crispness indicator of dry crispy food. *Journal of Texture Studies, 51*(2), 232-241. https://doi.org/https://doi.org/10.1111/jtxs.12485

Edwards, J. S. A., Meiselman, H. L., Edwards, A., & Lesher, L. (2003). The influence of eating location on the acceptability of identically prepared foods. *Food Quality and Preference, 14*(8), 647-652. https://doi.org/10.1016/s0950-3293(02)00189-1

Fink, D. (2017). Disability rights aspects of ambient noise for people with auditory disorders under the Americans with Disabilities Act (ADA). In proceedings of Meetings on Acoustics, New Orleans, LA.

Furnham, A., & Strbac, L. (2002). Music is as distracting as noise: the differential distraction of background music and noise on the cognitive test performance of introverts and extraverts. *Ergonomics, 45*(3), 203-217. https://doi.org/10.1080/00140130210121932

Hannum, M., Forzley, S., Popper, R., & Simons, C. T. (2019). Does environment matter? Assessments of wine in traditional booths compared to an immersive and actual wine bar. *Food Quality and Preference, 76*, 100-108. https://doi.org/https://doi.org/10.1016/j.foodqual.2019.04.007

Hannum, M. E., & Simons, C. T. (2020). Development of the engagement questionnaire (EQ): A tool to measure panelist engagement during sensory and consumer evaluations. *Food Quality and Preference, 81*, 103840. https://doi.org/10.1016/j.foodqual.2019.103840

Hoppe, U., Hast, A., & Hocke, T. (2015). Audiometry-based screening procedure for cochlear implant candidacy. *Otology & Neurotology, 36*(6), 1001-1005. https://doi.org/10.1097/MAO.0000000000000730

Hummel, T., Konnerth, C. G., Rosenheim, K., & Kobal, G. (2001). Screening of olfactory function with a four-minute odor identification test: reliability, normative data, and investigations in patients with olfactory loss. *Annals of Otology, Rhinology & Laryngology, 110*(10), 976-981. https://doi.org/10.1177/000348940111001015

Jarma Arroyo, S. E., Hogan, V., Ahrent Wisdom, D., Moldenhauer, K. A. K., & Seo, H. S. (2020). Effect of geographical indication information on consumer acceptability of cooked aromatic rice. *Foods, 9*(12), 1843. https://doi.org/10.3390/foods9121843

Kong, Y., Sharma, C., Kanala, M., Thakur, M., Li, L., Xu, D., Harrison, R., & Torrico, D. D. (2020). Virtual reality and immersive environments on sensory perception of chocolate products: a preliminary study. *Foods, 9*(4), 515. https://doi.org/10.3390/foods9040515

Kremer, S., Bult, J. H., Mojet, J., & Kroeze, J. H. (2007). Food perception with age and its relationship to pleasantness. *Chemical Senses, 32*(6), 591-602. https://doi.org/10.1093/chemse/bjm028

Landis, B. N., Welge-Luessen, A., Bramerson, A., Bende, M., Mueller, C. A., Nordin, S., & Hummel, T. (2009). "Taste Strips" - a rapid, lateralized, gustatory bedside identification test based on impregnated filter papers. *Journal of Neurology, 256*(2), 242-248. https://doi.org/10.1007/s00415-009-0088-y

Lazarus, H. (1986). Prediction of verbal communication is noise— a review: part 1. *Applied Acoustics*, *19*(6), 439-464. https://doi.org/10.1016/0003-682x(86)90039-3

Lebo, C. P., Smith, M. F., Mosher, E. R., Jelonek, S. J., Schwind, D. R., Decker, K. E., Krusemark, H. J., & Kurz, P. L. (1994). Restaurant noise, hearing loss, and hearing aids. *The Western Journal of Medicine*, *161*(1), 45-49. https://www.ncbi.nlm.nih.gov/pubmed/7941506

Lombard, E. (1911). The sign of the elevation of the voice. *Annales des Maladies de l'Oreille, du Larynx, du Nez et du Pharynx, 37*(2), 101–119.

Luckett, C. R., Meullenet, J.-F., & Seo, H.-S. (2016). Crispness level of potato chips affects temporal dynamics of flavor perception and mastication patterns in adults of different age groups. *Food Quality and Preference, 51*, 8-19. https://doi.org/10.1016/j.foodqual.2016.02.013

Madans, J. H., Weeks, J. D., & Elgaddal, N. (2021). *Hearing Difficulties Among Adults: United States, 2019* (Vol. 414). National Center for Health Statistics.

Miles, K., Beeches, T., Best, V., & Buchholz, J. (2022). Measuring speech intelligibility and hearing-aid benefit using everyday conversational sentences in real-world environments. *Frontiers in Neuroscience, 16*, 789565. https://doi.org/10.3389/fnins.2022.789565

Moir, J. (2015). *Why are restaurants so noisy? Can't hear a word your other half says when you dine out? Our test proves restaurants can be a loud as rock concerts.* Retrieved December 14, 2022 from http://www.dailymail.co.uk/news/article-3346929/Why-restaurants-noisy-thear-word-half-says-dine-test-proves-restaurants-loud-rock-concerts.html

Mosher, E. R., & Jelonek, S. J. (1991). Real ear measurement of noise and aided performance in noise. American Speech, Hearing, and Language Association meeting, Atlanta, GA.

North, A. C., & Hargreaves, D. J. (1998). The effect of music on atmosphere and purchase intentions in a cafeteria. *Journal of Applied Social Psychology*, *28*(24), 2254-2273. https://doi.org/10.1111/j.1559-1816.1998.tb01370.x

North, A. C., Sheridan, L. P., & Areni, C. S. (2016). Music congruity effects on product memory, perception, and choice. *Journal of Retailing, 92*(1), 83-95. https://doi.org/10.1016/j.jretai.2015.06.001

North, A. C., Shilcock, A., & Hargreaves, D. J. (2016). The effect of musical style on restaurant customers' spending. *Environment and Behavior, 35*(5), 712-718. https://doi.org/10.1177/0013916503254749

Ozimek, E., Kutzner, D., Sęk, A., & Wicher, A. (2009). Development and evaluation of polish digit triplet test for auditory screening. *Speech Communication, 51*(4), 307-316. https://doi.org/10.1016/j.specom.2008.09.007

Pieniak, M., Lachowicz-Tabaczek, K., Masalski, M., Hummel, T., & Oleszkiewicz, A. (2020). Self-rated sensory performance in profoundly deaf individuals. Do deaf people share the conviction about sensory compensation? *Journal of Sensory Studies, 35*(4), e12572. https://doi.org/10.1111/joss.12572

Raab, C., Zemke, D. M. V., Hertzman, J. L., & Singh, D. (2013). Restaurant customers' perceptions of noise and their satisfaction and loyalty behaviors. *International Journal of Hospitality & Tourism Administration, 14*(4), 398-414. https://doi.org/10.1080/15256480.2013.838090

Rahne, T., Koppke, R., Nehring, M., Plontke, S. K., & Fischer, H. G. (2018). Does ambient noise or hypobaric atmosphere influence olfactory and gustatory function? *PLoS One, 13*(1), e0190837. https://doi.org/10.1371/journal.pone.0190837

Roy, K. P., & Siebein, K. (2019). Satisfying hunger, thirst, and acoustic comfort in restaurants, diners, and bars... Is this an oxymoron? *Acoustics Today, 15*(2), 20-28. https://acousticstoday.org/issues/2019AT/Summer2019/

Salvador, A., Varela, P., Sanz, T., & Fiszman, S. M. (2009). Understanding potato chips crispy texture by simultaneous fracture and acoustic measurements, and sensory analysis. *LWT - Food Science and Technology, 42*(3), 763-767. https://doi.org/https://doi.org/10.1016/j.lwt.2008.09.016

Seo, H. S., Hahner, A., Gudziol, V., Scheibe, M., & Hummel, T. (2012). Influence of background noise on the performance in the odor sensitivity task: effects of noise type and extraversion. *Experimental Brain Research, 222*(1-2), 89-97. https://doi.org/10.1007/s00221-012-3222-5

Sester, C., Deroy, O., Sutan, A., Galia, F., Desmarchelier, J.-F., Valentin, D., & Dacremont, C. (2013). "Having a drink in a bar": An immersive approach to explore the effects of context on drink choice. *Food Quality and Preference, 28*(1), 23-31. https://doi.org/10.1016/j.foodqual.2012.07.006

Sinesio, F., Moneta, E., Porcherot, C., Abbà, S., Dreyfuss, L., Guillamet, K., Bruyninckx, S., Laporte, C., Henneberg, S., & McEwan, J. A. (2019). Do immersive techniques help to capture consumer reality? *Food Quality and Preference, 77*, 123-134. https://doi.org/10.1016/j.foodqual.2019.05.004

Smits, C., Kapteyn, T. S., & Houtgast, T. (2004). Development and validation of an automatic speech-in-noise screening test by telephone. *International Journal of Audiology, 43*(1), 15-28. https://doi.org/10.1080/14992020400050004

Spence, C. (2014). Noise and its impact on the perception of food and drink. *Flavour, 3*(1). https://doi.org/10.1186/2044-7248-3-9

Spence, C., Michel, C., & Smith, B. (2014). Airplane noise and the taste of umami. *Flavour, 3*(1), 2. https://doi.org/10.1186/2044-7248-3-2

Spence, C., Reinoso-Carvalho, F., Velasco, C., & Wang, Q. J. (2019). Extrinsic auditory contributions to food perception & consumer behaviour: an interdisciplinary review. *Multisensory Research, 32*(4-5), 275-318. https://doi.org/10.1163/22134808-20191403

Stelick, A., Penano, A. G., Riak, A. C., & Dando, R. (2018). Dynamic context sensory testing-a proof of concept study bringing virtual reality to the sensory booth. *Journal of Food Science, 83*(8), 2047-2051. https://doi.org/10.1111/1750-3841.14275

Trautmann, J., Meier-Dinkel, L., Gertheiss, J., & Morlein, D. (2017). Noise and accustomation: A pilot study of trained assessors' olfactory performance. *PLoS One, 12*(4), e0174697. https://doi.org/10.1371/journal.pone.0174697

Valente, M., & Mispagel, K. M. (2008). Unaided and aided performance with a directional open-fit hearing aid. *International Journal of Audiology, 47*(6), 329-336. https://doi.org/10.1080/14992020801894832

Wang, Q., & Spence, C. (2015). Assessing the influence of the multisensory atmosphere on the taste of vodka. *Beverages, 1*(3), 204-217. https://doi.org/10.3390/beverages1030204

Wilson, S. (2016). The effect of music on perceived atmosphere and purchase intentions in a restaurant. *Psychology of Music, 31*(1), 93-112. https://doi.org/10.1177/0305735603031001327

Woods, A. T., Poliakoff, E., Lloyd, D. M., Kuenzel, J., Hodson, R., Gonda, H., Batchelor, J., Dijksterhuis, G. B., & Thomas, A. (2011). Effect of background noise on food perception. *Food Quality and Preference, 22*(1), 42-47. https://doi.org/10.1016/j.foodqual.2010.07.003

Young, V., & Mihailidis, A. (2010). Difficulties in automatic speech recognition of dysarthric speakers and implications for speech-based applications used by the elderly: a literature

review. *Assistive Technology*, *22*(2), 99-112; quiz 113-114.
https://doi.org/10.1080/10400435.2010.483646

Chapter 6- Development of a sensory intervention for improving the acceptance of food in individuals with hearing loss

Abstract

Sensory interventions have proven to be a beneficial tool to improve food acceptance and food intake of consumer segments with sensory losses. This study proposed flavor enhancement or intensification to increase hedonic acceptance of food for individuals with hearing loss. Two increasing concentrations (30% and 60% flavor increments) of orange juice and a control (no flavor increment) were presented to participants with hearing loss (HL) and with normal hearing (NH). The two hearing groups were asked to taste the three samples and rate them in terms of overall acceptance, just-about-right flavor intensity, and rank the samples in terms of preference. Results of this intervention showed that HL individuals preferred the orange juice sample with a 30% flavor increment over the orange juice with no flavor increment. Contrastingly, NH individuals did not show a significant difference in their preference for any of the three flavor treatments. NH individuals also considered the 30% and 60% flavor increments to have too much flavor intensity. Thus, this study shows that flavor enhancement can be employed as a successful strategy to improve the hedonic acceptance of food in the segment of consumers with hearing loss. This study also hopes to encourage food developers and scientists to utilize flavor intensification as strategy that could benefit consumers with hearing losses without having a negative impact on sensory acceptance among consumers with normal hearing.

Keywords: intervention, flavor enhancement, hearing loss, sensory.

1. Introduction

Hearing loss may cause a profound impact on quality of life (QoL). Consequences for the social, functional, and psychological well-being of the affected persons have been extensively documented; including greater chances of depression, anxiety, social isolation, and cognitive decline (Gopinath et al., 2012; Ciorba et al., 2012; Carlsson et al., 2014; Wallhagen et al., 2006). According to the American Dietetic Association (Niedert, 2005), even though sometimes overlooked, food is an essential component of quality of life. An unacceptable or unpalatable diet can lead to poor food and fluid intake, resulting in weight loss, undernutrition, and a spiral of negative health effects (American Dietetic Association, 2005). As a result, Grunert et al. (2007) have proposed the inclusion of satisfaction to food-related-life as an additional domain to the current QoL measurements. Satisfaction with food-related life is defined as a part of a person's life comprising procurement, preparation and consumption of food and meals according to his/her chosen criteria (Grunert et al., 2007). For individuals with sensory deficiencies, food-related QoL has shown to be impacted due to the eating and food-related difficulties that come along with the sensory loss. For example, Ferris and Duffy (1989) found that 69% of patients with olfactory loss reported a decreased in food enjoyment after onset of the olfactory disorder. Similarly, Vági et al. (2012) found that blind and visually impaired individuals described a variety of problems in shopping for food and preparing it for consumption. However, to date there were no studies exploring the effects of hearing loss on perceived food satisfaction and/or eating habits. It has been proven on the previous chapter of this dissertation that hearing loss can significantly impact their enjoyment and perception of food.

In recent years, there has been a growing interest on the development of interventions that improve the food-related QoL among segments of the population with various sensory impairments. Numerous efforts in this regard have been located to the elderly segment of the population, due to the increase prevalence of sensory loss in higher ages (Schiffman, 1983, 1993, 1997; Doty et al., 1984; Stevens et al., 1995; Cain & Gent, 1991; Murphy, 1993). The Five-Aspect Meal (FAM) model is a meal optimization tool originally developed by Gustafsson et al. (2006) for planning service delivery that enhance customers' satisfaction in restaurants. This model is valuable to understand and handle the various aspects involved in a meal for people with sensory loss and to optimize their meal consumption (Gustafsson et al., 2006). The FAM model states that the handle and care of five main aspects of the meal consumption, such as the product (food adapted to meet sensory acceptability), the room setting (physical environment), the meeting (social company), the atmosphere (removal of stressful cues), and the management control system (organization around the meal) can significantly improve consumers' overall enjoyment of food. Most research on interventional strategies for sensory impaired people has focused on managing one single aspect of the FAM model at the time, rather than exploring meal consumption as a holistic experience with many moving parts playing a role (Gustafsson et al., 2006). For individuals with hearing loss environmental modifications have been suggested as a matter of intervention to enhance comprehension and minimize the impact of background noise in speech perception. For example, Larbsy et al. (2005) suggested that in a restaurant, it may be helpful for the person with hearing loss to sit with his back to the wall, so the sound does not come from all sides. In addition, the researchers recommend that individuals with hearing loss should not sit at the end of a table or away from the center of conversation and that they should find a place where there is light enough to allow faces to be seen because visual cues are helpful (Larbsy et al., 2005).

With respect to the product aspect of the FAM model, a common coping strategy for sensory loss treatments is enriching food by highlighting other sensory information other than the one affected (Croy et al., 2014). For example, Croy et al. (2004) suggested that for individuals with olfactory loss, enhancing food sensory attributes such as texture and color could improve smell-impaired individuals' eating quality. On the other hand, for visually-impaired individuals' sensory aspects liked taste and flavor were essential cues for food choice decisions, product acceptance, and food intake (Kostyra et al., 2017). For individuals with hearing loss, Chapter 4 demonstrated that aspects such as flavor intensity are not perceived as intensely as individuals with normal hearing. Thus, changes in the flavor intensity could serve as an effective product intervention for this segment of the population. The objective of this study was to develop and apply interventional strategies that improve individuals with hearing loss sensory acceptability of food. The focus of this intervention is related to the product aspect of the FAM model. More specifically, a flavor enhancement intervention was proposed to improve individuals with hearing loss overall acceptance of food.

2. Materials and Methods

This study was conducted in conformance with the Declaration of Helsinki for studies on human subjects. The protocol used in this was approved by the Institutional Review Board of the University of Arkansas (Fayetteville, AR, USA). Written informed consent was obtained from each participant before participation.

2.1. Participants

Table 1 shows participants' demographic profiles. A total of 16 individuals with hearing loss (HL) (based on self-report diagnoses) [8 females and 8 males; mean age ± standard deviation (SD) = 63 ± 13 years old], and 16 individuals with normal hearing (NH) [7 females and 9 males;

mean age ± standard deviation (SD) = 60 ± 9 years old] were recruited via a consumer profile database of the University of Arkansas Sensory Science Center, hearing clinics, deaf clubs, and the University of Arkansas campus. HL and NH groups did not significantly differ in terms of mean age ($P = 0.46$) and gender ratio ($P = 1.00$). Volunteers who reported having dentures, food allergies, other sensory deficiencies or cognitive impairments were not included in the study. Eight (50.0%) of HL participants that participated in this study had been diagnosed with a sensorineural hearing loss, 14 (87.6%) of HL individuals had a moderate (41 to 55 dB HL) or higher degree of hearing loss and 11 (68.8%) of them indicated having a high-frequency hearing loss configuration. In addition, approximately 56.3% indicated wearing a hearing assistive device such as hearing aids. All NH individuals showed evidence of normal auditory status assessed via the adult hearing screening procedure recommended by the American Speech-Language-Hearing Association (ASHA, 2022) (refer to Chapter 3 for details on the hearing screening procedure).

2.2. Food samples

Doets et al. (2016) indicated that successful strategies to maintain interest in food have to be developed to improve the quality and quantity of food intake in individuals with sensory impairments. One major aspect of these strategies involves developing and offering food products that meet the needs and wants of the affected consumer segment (Doets et al., 2016). Enhancement of the food sensory attributes has shown to compensate for sensory losses and to increase food liking and food intake. Thus, in this study a series of three products were developed based on a unisensory enhancement (i.e., flavor intensity). Orange juice concentrate was chosen as the selected food product to be modified based on the results of Chapter 4. A series of three dilutions of Minute Maid Frozen Orange Juice Concentrate (The Coca-Cola Co., Atlanta, GA, USA) were created representing increments of 30% and 60% from the original dilution (control) as shown in

Table 2. For succinctness purposes, throughout the manuscript, the 30% and 60% flavor increment treatments will be referred to as 30FLV and 60FLV, respectively.

2.3.Procedure

Experimental instructions and scales were presented using sensory evaluation software, Compusense Cloud® (Compusense Inc., Guelph, ON, Canada). Participants were presented with the three orange juice samples, in a sequential monadic fashion, randomized using a Williams Latin square design (Williams, 1949). Each of the three samples was served in a 118- mL souffle cup (Dart Container Corporation, Mason, MI, USA) with a lid, identified by a 3-digit code, at a temperature of approximately 4 °C. Participants were asked to rate overall liking on a 9-point hedonic scale ranging from 1 (dislike extremely) to 9 (like extremely). Participants also rated the flavor intensity of the samples on a 7-point Just-About-Right (JAR) scale (1 = much too little, 4 = JAR, and 7 = much too much). After tasting all samples, participants were presented with all samples again all at once and were asked to rank them in order of preference. Between sample presentations, a 240-mL of bottled water (Nestle Waters North America, Stamford, CT, USA) and unsalted crackers (Nabisco Premium, Mondēlez International, East Hanover, NJ, USA) were provided to participants for palate cleansing.

2.4.Statistical Analysis

Statistical analyses were performed using XLSTAT software (Addinsoft, New York, NY, USA). To determine if an increase in flavor concentration could improve the hedonic ratings of individuals with hearing loss a Kruskal-Wallis test was conducted for each hearing group. If a significant effect was identified among the flavor enhancement treatments, post hoc multiple pairwise comparisons between independent variables were conducted using Mann-Whitney test.

For the JAR scale data, a penalty analysis was used to identify how much flavor increments affected the overall liking of cooked rice samples. JAR was determined when the percentage of the JAR score was greater than 70%, and no more than 20% of responses were on either minus (-) or plus (+) side of the scale (Choi et al., 2018).

Kruskal-Wallis test was employed to analyze the preference ranking data for each hearing group. If a significant difference was detected by the Kruskal-Wallis test multiple comparisons between the independent variables were conducted using Wij's procedure (Brockhoff & Linander, 2017). For all analyses, a statistically significant difference was defined as $P < 0.05$.

3. Results

As shown in Figure 1, the Kruskal-Wallis test revealed no significant effect of 'food sample' on the overall liking ratings of the HL group ($P = 0.13$). In addition, no significant effect of 'food sample' was found for the overall acceptance ratings of NH individuals ($P = 0.95$) (Figure 1). Even though not statistically significant, for the HL group the acceptance mean of the 30FLV treatment was higher, followed by the control sample and finally the 60FLV treatment. Contrastingly, an opposite trend was observed in the NH group where higher concentrations obtained lower acceptance scores. However, these differences were also not statistically significant.

Figure 2 shows the sum rankings for the preference ranking data as evaluated by HL and NH groups. A Kruskal-Wallis test showed that there was a significant difference in preference rankings between the orange juice samples for the HL group with regards to overall preference ($\chi^2 = 9.00$, $P = 0.01$). More specifically, HL individuals significantly preferred the 30FLV treatment over the control. However, no significant differences in preference were observed between the 60FLV treatment and the control or the 30FLV treatment. Contrastingly, a Kruskal-

Wallis test revealed no significant differences between the orange juice samples in the NH group with respect to preference ranking (P = 0.84).

As shown in Table 3, a penalty analysis on the JAR flavor scores showed that 25% of NH individuals penalized the 30FLV treatment, for having ‘too much’ flavor significantly dropping the overall liking mean by 1.92 points. Moreover, 50% of normal hearing individuals considered that the 60FLV treatment had ‘too much’ flavor, further dropping the overall liking mean 2.02 points. On the other hand, 25% of HL individuals penalized the 30FLV treatment, for having ‘too little’ flavor significantly dropping the overall liking mean by 1.80 points. In addition, no significant flavor penalties were found on the 60FLV treatment by the HL group (Table 3).

4. Discussion

To the best of authors’ knowledge, this is the first study to assess the employment of flavor intensification as an intervention tool to increase food acceptance in individuals with hearing loss. This study showed that individuals with hearing loss perceived the flavor intensity of orange juice lower than individuals with normal hearing, further decreasing the group with hearing loss overall acceptance. This intervention study showed that flavor-enhancement resulted in an increase of orange juice preference for participants with hearing loss. More specifically individuals with hearing loss preferred an increment of 30% in orange juice flavor compared to the control (no flavor enhancement). This was not the case for hearing controls where little differences in preference were observed across the flavor enhancement treatments. These findings are in agreement with previous studies showing benefits of flavor enhancement on the acceptance of food for populations with sensory losses (Schiffman, 1988; Schiffman & Warwick, 1993; Schiffman, 2000; Schiffman et al., 2007). For example, Schiffman (2000) found that flavor intensification increased sensory acceptance of and positive emotional responses to foods (carrots, green beans, green peas, potatoes, turkey, chicken, chicken soup, tomato soup, and vegetable soup) in cancer patients with diminished taste and smell functioning. Similarly, it has been proposed that flavor enhancers be used to make up for the lowered chemosensory functioning that contributes to the so-called "anorexia of aging," or the decreased control of hunger in elderly people (Schiffman & Warwick, 1988). One explanation to this phenomenon lies on the fact that enhancing flavor could bring back foods hedonic functions and encourage a partial return to this population's initial attitudes and behavioral responses to eating (Mathey et al., 2001). Previous research also suggests that eating flavor enhanced foods activates the limbic system and endogenous opioid activity, which could explain the increase in positive affect (Schiffman & Warwick, 1988).

Benefits of improving hedonic acceptance of food go beyond the eating sensory experience and may also increase food intake and nutritional status of said populations. Even though this study did not include any eating behavior measurements, previous research has shown an intrinsic relationship between hedonic responses and food intake. Mathey et al. (2001) found that adding flavor enhancers to cooked meals was an effective way to improve dietary intake and body weight in elderly nursing home residents. Thus, if the flavor enhanced meal approach is used in highly nutritious foods, then an additional health benefit could be obtained. Indeed, humans as other animals, learn to eat in response to sensory cues by creating associations between the early sensory characteristics of a food and the post ingestive effects of nutrient delivery. In turn, increased preferences for nutrient-rich foods and attitudes towards a food sensory properties would affect food intake and selection.

Taken together, the results from this study suggest that flavor intensification is a feasible alternative for the improvement of food acceptance in individuals with hearing loss. Food, though sometimes overlooked, is an essential part of life. Therefore, an increase in food acceptance is crucial for the overall enjoyment of life, especially for populations with sensory losses. Naturally, due to the large importance that smells have in the eating experience, among all sensory disorders, olfactory impairment have been the main focus in the literature regarding the relationship between quality of life (QoL) and food enjoyment (see also Seo et al., 2021). For example, Ferris and Duffy found that 69% of their patients enjoyed food less than before onset of the disorder (Ferris & Duffy 1989). The reduced experience of food quality led to diminished appetite in 27% of their patients. However, as other authors have reported coping mechanisms such as eating after time schemes and enriching food by other sensory information, such as taste, texture, and color, are often reported to be helpful in increasing food enjoyment and in turn QoL (Croy et al., 2014). The current study showed that similar benefits can be obtained for people with hearing loss, encouraging consumers with hearing loss to use flavor enhancement mechanisms to improve their overall QoL.

From a food company's perspective, developing food products that suit a small segment of consumers might not be a top priority to the corporation due to their inherent profit-driven nature. However, this study showed that strategies like flavor intensification could improve food enjoyment of consumers with sensory losses without negatively impacting the general consumer segment acceptance. Certainly, this, as other interventional strategies, shall not be generalized to every food product and have to be evaluated in a case-by-case basis. In addition, from a scientific perspective sensory and food scientists should share the social responsibility to consider marginal populations in their research. As Gómez-Corona (2020) indicated in his review, the role of a sensory scientist, as other scientists, should aim to positively impact the life of humas, animals and the environment. In other words, our research output ought to be beneficial to society and synergistic with the natural world. An excellent manner of achieving this is by exploring research areas that include people with disabilities such as people with hearing loss as this study has, visually impaired individuals (Gómez-Corona et al., 2020), elderly populations (Vandenberghe-Descamps et al., 2017; Liu et al., 2022), or neurodiverse individuals (Cermak et al., 2020; Chistol et al., 2018; Nadon et al., 2011).

Finally, it should be noted that although flavor enhancement was successful in increasing sensory preference in the group with hearing loss, a multisensory rather than a unisensory approach as suggested by the FAM model could have possibly obtained higher hedonic ratings. As demonstrated in Chapters 3 and 5, other aspects of the food consumption experience such as the texture of food and contextual/environmental cues can also greatly impact consumers with hearing loss food enjoyment. Thus, changes in textural attributes of food and optimization of background noise levels should be explored in the future individually and in conjunction as interventional tools to improve overall food enjoyment.

5. Conclusions

Based on this study, we recommend flavor intensification as a great alternative for the improvement of food acceptance in individuals with hearing loss. As it was demonstrated, individuals with hearing loss preferred a 30% increment of orange juice flavor over the no enhancement treatment. This study also showed that individuals with normal hearing preferences and their hedonic scores were not negatively impacted by the flavor enhancement, making this type of interventional measure applicable to a practical scenario of product development in the food industry.

Table 1. Demographic profile of participants.

	Group with Normal Hearing		Group with Hearing Loss	
	N	%	*N*	%
Number of Participants	16		16	
Gender				
Men	8	50.0	7	
Women	8	50.0	9	
Mean Age (± Standard Deviation)				
Education Level[1]				
High school	2	12.5	3	18.8
Some college	1	6.3	5	31.3
2–4 year college degree	9	56.3	4	25.0
Master, or PhD degree	4	18.8	4	25.0
Annual Income (per year)				
<$20,000	0	0.0	1	6.3
$20,000 to $39,999	2	12.5	4	25.0
$40,000 to $59,999	3	18.8	3	18.8
$60,000 to $79,999	6	37.5	2	12.5
$80,000 to $99,999	5	31.3	2	12.5
>$100,000	0	0.0	4	25.0
Hearing Loss Type				
Conductive			6	37.5
Sensorineural			8	50.0
Mixed (conductive and sensorineural)			2	12.5
Hearing Loss Degree				
Mild			2	12.5
Moderate			7	43.8
Moderately Severe			4	25.0
Severe			1	6.3
Profound			2	12.5
Hearing Loss Configuration				
High Frequency			11	68.8
Middle Frequency			2	12.5
Low Frequency			3	18.8
Hearing Assistive Device Usage				
Hearing aids			9	56.3
Cochlear implants			0	0.0
Do not wear a HA device			7	43.8

Table 2. Series of orange juice concentrations employed in this study.

Sample[a]	Orange juice concentrate (mL)	Water (mL)
Control	354.9	946.4
30FLV	354.9	662.4
60FLV	354.9	378.5

[a]30FLV and 60 FLV, refers to 30% flavor increment treatment and 60% flavor increment treatment, respectively.

Table 3. Penalty analysis for each of the orange juice samples with respect to the flavor JAR scores evaluated by either individuals with normal hearing or with hearing loss.

	Sample[a]	Level	Frequencies (%)	Mean Drops	Penalties	*P*-value
Group with Normal Hearing	Control	not enough	31.25%	1.78	1.35	0.02
		JAR	56.25%			
		too much	12.50%	0.28		
	30FLV	not enough	18.75%	1.00	1.52	0.02
		JAR	56.25%			
		too much	25.00%	1.92		
	60FLV	not enough	6.25%	4.14	2.25	0.01
		JAR	43.75%			
		too much	50.00%	2.02		
Group with Hearing Loss	Control	not enough	37.50%	2.24	2.13	0.002
		JAR	43.75%			
		too much	18.75%	1.90		
	30FLV	not enough	25.00%	1.80	2.13	<0.001
		JAR	62.50%			
		too much	12.50%	2.80		
	60FLV	not enough	18.75%	1.67	1.87	0.11
		JAR	18.75%			
		too much	62.50%	1.93		

[a]30FLV and 60 FLV, refers to 30% flavor increment treatment and 60% flavor increment treatment, respectively.

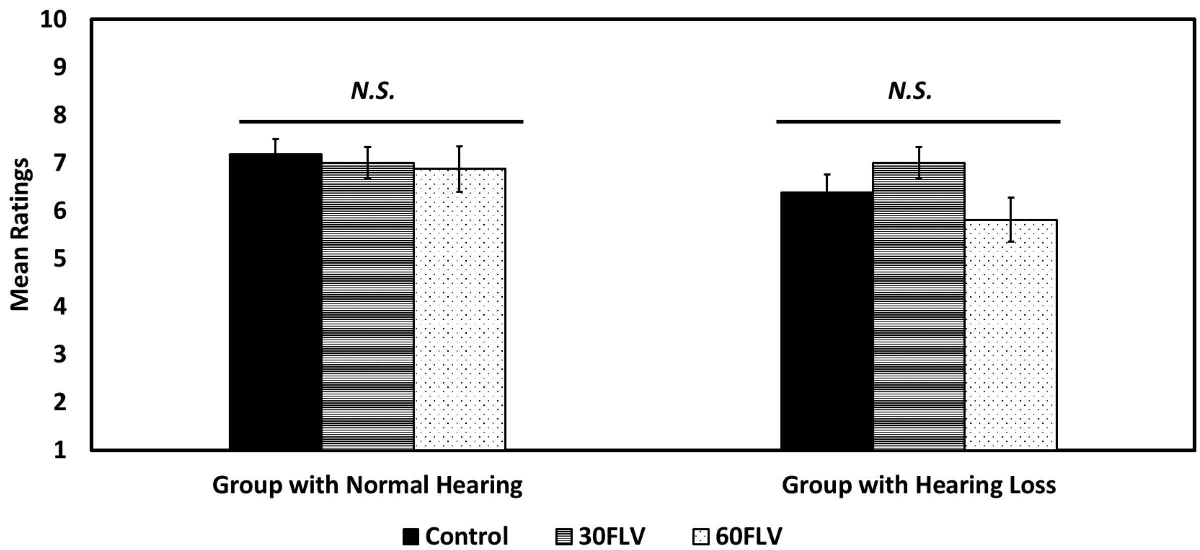

Figure 1. Acceptance ratings of orange juice samples evaluated by individuals with normal hearing and with hearing loss. Error bars represent standard errors of the means. *N.S.* represents no significant difference ($P > 0.05$). 30FLV and 60 FLV, refers to 30% flavor increment treatment and 60% flavor increment treatment, respectively.

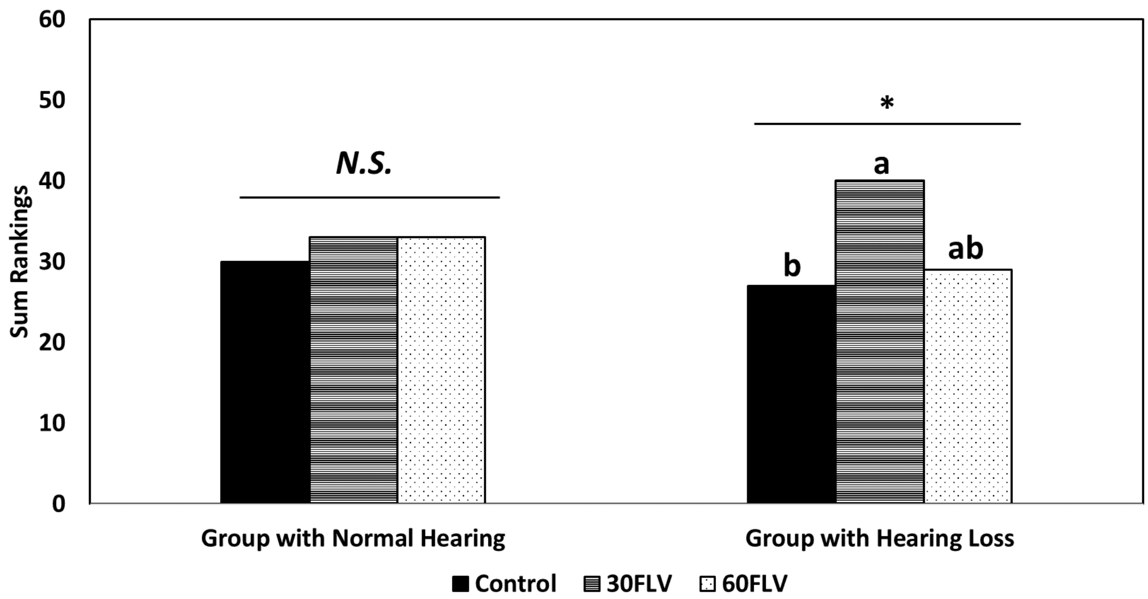

Figure 2. Preference sum rankings for the orange juice samples evaluated by individuals with normal hearing and with hearing loss. *N.S.* represents no significant difference ($P > 0.05$). *, indicates a significant difference at $P < 0.05$. Different letters within one category are significantly different at $P < 0.05$. 30FLV and 60 FLV, refers to 30% flavor increment treatment and 60% flavor increment treatment, respectively.

References

Brockhoff, P. B., & Linander, C. B. (2017). Analysis of the data using the R package sensR. In L. Rogers (Ed.), *Discrimination Testing in Sensory Science* (pp. 303-344). Woodhead Publishing. https://doi.org/10.1016/b978-0-08-101009-9.00015-0

Carlsson, P. I., Hjaldahl, J., Magnuson, A., Ternevall, E., Eden, M., Skagerstrand, A., & Jonsson, R. (2015). Severe to profound hearing impairment: quality of life, psychosocial consequences and audiological rehabilitation. *Disability and Rehabilitation, 37*(20), 1849-1856. https://doi.org/10.3109/09638288.2014.982833

Cermak, S. A., Curtin, C., & Bandini, L. G. (2010). Food selectivity and sensory sensitivity in children with autism spectrum disorders. *Journal of the American Dietetic Association, 110*(2), 238-246. https://doi.org/10.1016/j.jada.2009.10.032

Chistol, L. T., Bandini, L. G., Must, A., Phillips, S., Cermak, S. A., & Curtin, C. (2018). Sensory sensitivity and food selectivity in children with autism spectrum disorder. *Journal of Autism and Developmental Disorders, 48*(2), 583-591. https://doi.org/10.1007/s10803-017-3340-9

Choi, W. S., Jarma Arroyo, S. E., & Seo, H.-S. (2018). Cross-cultural comparisons between Korean and U.S. adults with respect to texture perception and acceptance of cooked milled rice. *International Journal of Food Science & Technology, 53*(9), 2181-2194. https://doi.org/10.1111/ijfs.13807

Ciorba, A., Bianchini, C., Pelucchi, S., & Pastore, A. (2012). The impact of hearing loss on the quality of life of elderly adults. *Clinical Interventions in Aging, 7*, 159-163. https://doi.org/10.2147/CIA.S26059

Croy, I., Nordin, S., & Hummel, T. (2014). Olfactory disorders and quality of life--an updated review. *Chemical Senses, 39*(3), 185-194. https://doi.org/10.1093/chemse/bjt072

Doets, E. L., & Kremer, S. (2016). The silver sensory experience – A review of senior consumers' food perception, liking and intake. *Food Quality and Preference, 48*, 316-332. https://doi.org/10.1016/j.foodqual.2015.08.010

Ferris, A. M., & Duffy, V. B. (1989). Effect of olfactory deficits on nutritional status. Does age predict persons at risk? *Annals of the New York Academy of Sciences, 561*, 113-123. https://doi.org/10.1111/j.1749-6632.1989.tb20975.x

Gómez-Corona, C. (2020). Sensory and consumer research for good: a review on social responsibility. *Current Opinion in Food Science, 33*, 115-123. https://doi.org/10.1016/j.cofs.2020.03.008

Gómez-Corona, C., Pohlenz, A., Cayeux, I., & Valentin, D. (2020). Panel performance and memory in visually impaired versus sighted panels. *Food Quality and Preference, 80*, 103807.

Gopinath, B., Schneider, J., Hickson, L., McMahon, C. M., Burlutsky, G., Leeder, S. R., & Mitchell, P. (2012). Hearing handicap, rather than measured hearing impairment, predicts poorer quality of life over 10 years in older adults. *Maturitas, 72*(2), 146-151. https://doi.org/10.1016/j.maturitas.2012.03.010

Grunert, K. G., Dean, M., Raats, M. M., Nielsen, N. A., Lumbers, M., & Food in Later Life, T. (2007). A measure of satisfaction with food-related life. *Appetite, 49*(2), 486-493. https://doi.org/10.1016/j.appet.2007.03.010

Gustafsson, I.-B., Ostrom, A., Johansson, J., & Mossberg, L. (2006). The Five Aspects Meal Model: a tool for developing meal services in restaurants. *Journal of Foodservice, 17*(2), 84-93. https://doi.org/10.1111/j.1745-4506.2006.00023.x

Kostyra, E., Zakowska-Biemans, S., Sniegocka, K., & Piotrowska, A. (2017). Food shopping, sensory determinants of food choice and meal preparation by visually impaired people. Obstacles and expectations in daily food experiences. *Appetite, 113*, 14-22. https://doi.org/10.1016/j.appet.2017.02.008

Kremer, S., Holthuysen, N., & Boesveldt, S. (2014). The influence of olfactory impairment in vital, independently living older persons on their eating behaviour and food liking. *Food Quality and Preference, 38*, 30-39. https://doi.org/10.1016/j.foodqual.2014.05.012

Larsby, B., Hallgren, M., Lyxell, B., & Arlinger, S. (2005). Cognitive performance and perceived effort in speech processing tasks: effects of different noise backgrounds in normal-hearing and hearing-impaired subjects. *Intrenational Journal of Audiology, 44*(3), 131-143. https://doi.org/10.1080/14992020500057244

Liu, F., Yin, J., Wang, J., & Xu, X. (2022). Food for the elderly based on sensory perception: A review. *Current Research in Food Science, 5*, 1550-1558. https://doi.org/10.1016/j.crfs.2022.09.014

Luckett, C. R., Meullenet, J.-F., & Seo, H.-S. (2016). Crispness level of potato chips affects temporal dynamics of flavor perception and mastication patterns in adults of different age groups. *Food Quality and Preference, 51*, 8-19. https://doi.org/10.1016/j.foodqual.2016.02.013

Mathey, M. F., Siebelink, E., de Graaf, C., & Van Staveren, W. A. (2001). Flavor enhancement of food improves dietary intake and nutritional status of elderly nursing home residents. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences, 56*(4), M200-205. https://doi.org/10.1093/gerona/56.4.m200

Nadon, G., Feldman, D. E., Dunn, W., & Gisel, E. (2011). Association of sensory processing and eating problems in children with autism spectrum disorders. *Autism Research and Treatment, 2011*, 541926. https://doi.org/10.1155/2011/541926

Niedert, K. C., & American Dietetic, A. (2005). Position of the American Dietetic Association: Liberalization of the diet prescription improves quality of life for older adults in long-term care. *Journal of the American Dietetic Association, 105*(12), 1955-1965. https://doi.org/10.1016/j.jada.2005.10.004

Schiffman, S., Sattely-Miller, E., Taylor, E., Graham, B., Landerman, L., Zervakis, J., Campagna, L., Cohen, H., Blackwell, S., & Garst, J. (2007). Combination of flavor enhancement and chemosensory education improves nutritional status in older cancer patients. *The journal of nutrition, health & aging, 11*(5), 439. https://www.proquest.com/openview/44a3b9be29817fcc1037f55a123365b5/1?pq-origsite=gscholar&cbl=28850

Schiffman, S. S. (2000). Intensification of sensory properties of foods for the elderly. *The Journal of Nutrition, 130*(4S Suppl), 927S-930S. https://doi.org/10.1093/jn/130.4.927S

Schiffman, S. S., & Warwick, Z. S. (1988). Flavor enhancement of foods for the elderly can reverse anorexia. *Neurobiology of Aging, 9*(1), 24-26. https://doi.org/10.1016/s0197-4580(88)80009-5

Schiffman, S. S., & Warwick, Z. S. (1993). Effect of flavor enhancement of foods for the elderly on nutritional status: food intake, biochemical indices, and anthropometric measures. *Physiology & Behavior, 53*(2), 395-402. https://doi.org/10.1016/0031-9384(93)90224-4

Seo, H.-S., Pramudya, R. C., Singh, A., & Hummel, T. (2021). Recent evidence for the impacts of olfactory disorders on food enjoyment and ingestive behavior. *Current Opinion in Food Science, 42*, 187-194. https://doi.org/https://doi.org/10.1016/j.cofs.2021.06.006

Vági, Z., Deé, K., Lelovics, Z., & Lakatos, É. (2012). Nutritional status of blind and visually impaired patients. *Zeitschrift für Gastroenterologie, 50*(05), A50-A82. https://doi.org/10.1055/s-0032-1312436

Vandenberghe-Descamps, M., Sulmont-Rosse, C., Septier, C., Feron, G., & Laboure, H. (2017). Using food comfortability to compare food's sensory characteristics expectations of elderly people with or without oral health problems. *Journal of Texture Studies, 48*(4), 280-287. https://doi.org/10.1111/jtxs.12250

Wallhagen, M. I., Pettengill, E., & Whiteside, M. (2006). Sensory impairment in older adults: Part 1: Hearing loss. *AJN The American Journal of Nursing, 106*(10), 40-48; quiz 48-49. https://doi.org/10.1097/00000446-200610000-00030

Chapter 7- General Conclusion

To summarize, findings from Chapter 3 found that hearing loss impacted the overall acceptance and perception of texture attributes with an intrinsic sound component such as crispness in solid foods and viscosity of liquid foods. Pitch intensity, specifically, was found as a significant negative contributor to the overall liking of solid food samples in individuals with hearing loss (HL). In addition, the discrimination of solid food samples with smaller differences in crispness was diminished by hearing loss. Furthermore, Chapter 3 showed that hearing loss impacted loudness perception of liquid foods. HL individuals rated liquid samples as less loud compared to individuals with normal hearing (NH). Next, Chapter 4 showed that auditory loss impacted the aroma, and flavor perception of food samples. More specifically, a decrease in flavor perception was observed in the HL individuals compared to the NH individuals. In addition, aroma, and flavor liking of food samples was lower in the HL group. However, little impact of hearing loss was observed on the overall enjoyment and perception of sweet, salty, sour, bitter, and umami solutions. Next, Chapter 5 found that HL individuals were less comfortable with the speech loudness of dining companions compared to their NH counterparts during social dining. Affective value and total engagement scores were also lower in the HL group compared to the NH group. Aspects such as having to raise their voices and speech intelligibility were mentioned by the HL group as reasons why they disliked the restaurant environment. In addition, Chapter 5 reaffirmed that results of Chapter 3 and 4 on the impacts of hearing loss on texture and flavor perception and acceptance in an immersive restaurant setting. More specifically, Chapter 5 found that texture liking of low crispness samples and flavor intensity scores of all food samples were lower in the HL group compared to the NH group. Lastly, Chapter 6 recommends flavor enhancement as a successful sensory intervention to improve sensory acceptance of food in HL individuals. In conclusion, this dissertation is the first study, to the best of authors knowledge, to explore the relationships between hearing loss and food perception and acceptance. Taken together, this dissertation emphasizes the social responsibility that sensory and food scientists alike have in developing new food products that improved population minorities' food acceptance and nutritional status. Though, food companies always have the underlying responsibility of profit this study demonstrated that sensory enhancements could be applied without sacrificing the hedonic acceptance of typical populations. Thus, food modifications that are accepted by a variety of consumer segments should always be considered. In addition, this dissertation fills in a gap in the literature with regards to practical interventions to improve sensory acceptance of food individuals with hearing loss. Previous research that have explored texture modification and flavor enhancements as interventions for the elderly have mostly focused on the chemosensory dysfunctions that come with age. Thus, this dissertation reaffirms the need for these approaches as the global population continues ageing and hearing loss becomes more prominent.

This dissertation have some limitations that should be acknowledged. Due to a high attrition rate (~43%), Chapters 5 and 6 had a considerably smaller sample size compared to Chapters 3 and 4. This could have led to an inadequate power of the observed effects calling for careful interpretation of these results. In addition, our sample of participants with hearing loss consisted of a wide range of consumers with different onsets of their hearing loss. Individuals with different hearing loss onsets could have widely different experiences that have shaped their perception of food. For example, individuals with an age-related hearing loss (presbycusis) would have preconceived ideas of the sensory attributes of a specific food product from when they had a normal hearing that individuals with a congenital hearing loss would not. Finally, due to a higher occurrence of hearing loss in seniors, our sample was mostly representative of middle-aged and elder populations. Thus, the generalization of these results to a younger demographic is prohibited.

List of Appendix Contents

Appendix 1. IRB Approval Letters

(A)

UNIVERSITY OF ARKANSAS

To:	Han-Seok Seo FDSC N-215
From:	Douglas J Adams, Chair IRB Expedited Review
Date:	02/08/2021
Action:	**Exemption Granted**
Action Date:	02/08/2021
Protocol #:	2012306334
Study Title:	The influence of auditory cues on sensory perception of food or beverage items

The above-referenced protocol has been determined to be exempt.

If you wish to make any modifications in the approved protocol that may affect the level of risk to your participants, you must seek approval prior to implementing those changes. All modifications must provide sufficient detail to assess the impact of the change.

If you have any questions or need any assistance from the IRB, please contact the IRB Coordinator at 109 MLKG Building, 5-2208, or irb@uark.edu.

cc: Sara E Jarma Arroyo, Investigator
Rachel Glade, Investigator

Page 1 of 1

(B)

UNIVERSITY OF ARKANSAS

To:	Han-Seok Seo
From:	Justin R Chimka, Chair IRB Expedited Review
Date:	08/16/2021
Action:	**Exemption Granted**
Action Date:	08/16/2021
Protocol #:	2108348008
Study Title:	The impact of auditory cues on sensory perception of food or beverage items

The above-referenced protocol has been determined to be exempt.

If you wish to make any modifications in the approved protocol that may affect the level of risk to your participants, you must seek approval prior to implementing those changes. All modifications must provide sufficient detail to assess the impact of the change.

If you have any questions or need any assistance from the IRB, please contact the IRB Coordinator at 109 MLKG Building, 5-2208, or irb@uark.edu.

cc: Sara Esther Jarma Arroyo, Investigator

Appendix 2. Informed Consent Forms

(A)

INFORMED CONSENT (for volunteers without hearing loss)

Title: The influence of auditory cues on sensory perception of food or beverage items

Researcher(s):
Han-Seok Seo, Ph.D., Faculty
Rachel Glade, Ph.D., Faculty
Sara Jarma Arroyo, Graduate student

University of Arkansas, CAFLS
Department of Food Science
2650 N. Young Avenue
Fayetteville, AR 72704
479-575-4778 (Seo)
hanseok@uark.edu (Seo); **rglade@uark.edu** (Glade);
sejarmaa@uark.edu (Jarma Arroyo)

Administrator:
Ro Windwalker, CIP
IRB Coordinator
Office of Research Compliance
109 MLKG Building
University of Arkansas
Fayetteville, AR 72701
479-575-2208
irb@uark.edu

Description: This study aims to determine how auditory cues can affect consumer perception and liking of foods and beverage items. This study is composed of two sessions on two different days. Thus, you should visit the University of Arkansas Sensory Science Center twice. For each session, it will take approximately 30-40 minutes to complete the evaluation. You will be also asked to refrain from smoking, eating, and drinking for 2 hours prior to your evaluation; drinking water is allowed. During the study, you will be asked to evaluate the test samples (foods and beverage items) in terms of sensory perception (e.g., appearance, smell, taste, and texture, etc.), acceptance, and evoked emotions. Also, to measure emotional responses to the test samples, your facial expression and behavior will be recorded. You will be also asked to fill out questionnaires regarding demographics, emotions, and behavioral characteristics.

Risks and Benefits: All food and beverage samples presented in this study are prepared with commercially available ingredients or products. However, if you have known allergies or intolerances for specific ingredients or foods, please describe them here: ________________________.

After completing all two sessions (on two different days), you will receive the Amazon e-gift card ($40) as monetary reward.

Voluntary Participation: Your participation in the research is completely voluntary. The voluntary participation, i.e., choosing to participate or not, will have no effect on your relationship with the researchers or the University in any way.

Confidentiality: Your information on identity (e.g., name) will be coded as number (e.g., 1, 2, 3, etc.). The code number will be matched with your responses; that is, your data will be recorded anonymously. All information will be kept confidential to the extent allowed by law and University policy. Results from the research will be reported as aggregate data.

Right to Withdraw: You are free to refuse to participate in the research and to withdraw from this study at any time. Your decision to withdraw will bring no negative consequences — no penalty to you.

Informed Consent: I, the undersigned, have read the description, including the purpose of the study, the procedures to be used, the potential risks, the confidentiality, as well as the option to withdraw from the study at any time. Each of these items has been explained to me by the investigator. The investigator has answered all of my questions regarding the study, and I believe I understand what is involved. My signature below indicates that I freely agree to participate in this study and that I have received a copy of this agreement from the investigator. To minimize any potential risks of COVID-19, I will sign on this electronic form by printing my name and describing the date below, instead of signing on the paper form:

____ ______________________

Signature of the participant **Date**

If you have questions or concerns about this study, please contact one of the researchers listed above. For questions or concerns about your rights as a research participant, please contact the University's IRB Coordinator listed as "Administrator" above.

IRB # 2012306334 Approval Date: 02/08/2021

(B)

INFORMED CONSENT (for volunteers with hearing loss)

Title: The influence of auditory cues on sensory perception of food or beverage items

Researcher(s):
Han-Seok Seo, Ph.D., Faculty
Rachel Glade, Ph.D., Faculty
Sara Jarma Arroyo, Graduate student

University of Arkansas, CAFLS
Department of Food Science
2650 N. Young Avenue
Fayetteville, AR 72704
479-575-4778 (Seo)
hanseok@uark.edu (Seo); **rglade@uark.edu** (Glade);
sejarmaa@uark.edu (Jarma Arroyo)

Administrator:
Ro Windwalker, CIP
IRB Coordinator
Office of Research Compliance
109 MLKG Building
University of Arkansas
Fayetteville, AR 72701
479-575-2208
irb@uark.edu

Description: This study aims to determine how auditory cues can affect consumer perception and liking of foods and beverage items. This study is composed of two sessions on two different days. Thus, you should visit the University of Arkansas Sensory Science Center twice. For each session, it will take approximately 30-40 minutes to complete the evaluation. You will be also asked to refrain from smoking, eating, and drinking for 2 hours prior to your evaluation; drinking water is allowed. During the study, you will be asked to evaluate the test samples (foods and beverage items) in terms of sensory perception (e.g., appearance, smell, taste, and texture, etc.), acceptance, and evoked emotions. Also, to measure emotional responses to the test samples, your facial expression and behavior will be recorded. You will be also asked to fill out questionnaires regarding demographics, emotions, and behavioral characteristics.

Risks and Benefits: All food and beverage samples presented in this study are prepared with commercially available ingredients or products. However, if you have known allergies or intolerances for specific ingredients or foods, please describe them here: ________________________.

After completing all two sessions (on two different days), you will receive the Amazon e-gift card ($40) as monetary reward. For those with hearing loss, if you need an interpreter for your transportation and/or communication with researchers, your translator/helper will receive another Amazon e-gift card ($10) for each session ($20 for two sessions).

Voluntary Participation: Your participation in the research is completely voluntary. The voluntary participation, i.e., choosing to participate or not, will have no effect on your relationship with the researchers or the University in any way.

Confidentiality: Your information on identity (e.g., name) will be coded as number (e.g., 1, 2, 3, etc.). The code number will be matched with your responses; that is, your data will be recorded anonymously. All information will be kept confidential to the extent allowed by law and University policy. Results from the research will be reported as aggregate data.

Right to Withdraw: You are free to refuse to participate in the research and to withdraw from this study at any time. Your decision to withdraw will bring no negative consequences — no penalty to you.

Informed Consent: I, the undersigned, have read the description, including the purpose of the study, the procedures to be used, the potential risks, the confidentiality, as well as the option to withdraw from the study at any time. Each of these items has been explained to me by the investigator. The investigator has answered all of my questions regarding the study, and I believe I understand what is involved. My signature below indicates that I freely agree to participate in this study and that I have received a copy of this agreement from the investigator. To minimize any potential risks of COVID-19, I will sign on this electronic form by printing my name and describing the date below, instead of signing on the paper form:

____ ________________________

Signature of the participant **Date**

Informed Consent: I, _____________________________________ (please print), affirm that I have accurately presented the information in this consent document to the 'Participant' listed above and answered any questions to her/his understanding. To minimize any potential risks of COVID-19, I will sign on this electronic form by printing my name and describing the date below, instead of signing on the paper form:

____ ________________________

Signature of the interpreter **Date**

If you have questions or concerns about this study, please contact one of the researchers listed above. For questions or concerns about your rights as a research participant, please contact the University's IRB Coordinator listed as "Administrator" above.

IRB # 2012306334 Approval Date: 02/08/2021

(C)

INFORMED CONSENT

Title: The impact of auditory cues on sensory perception of food or beverage items

Researcher(s):
Han Seok Seo, Ph.D., Faculty
Sara Jarma Arroyo, Graduate student

University of Arkansas, CAFLS
Department of Food Science
2650 N. Young Avenue
Fayetteville, AR 72704
479-575-4778 (Seo)
hanseok@uark.edu (Seo); **sejarmaa@uark.edu** (Jarma Arroyo)

Administrator:

Ro Windwalker, CIP
IRB Coordinator
Office of Research Compliance
109 MLKG Building
University of Arkansas
Fayetteville, AR 72701
479-575-2208
irb@uark.edu

Description: This study aims to determine whether auditory cues can affect consumer perception and liking of food or beverage items. You will be asked to taste and evaluate food and/or beverage samples in terms of appearance, smell, taste, texture, hedonic impression, and evoked-emotion while wearing a headphone, in the presence (or absence) of background sounds at the Sensory Science Center. You will also be asked to fill out questionnaires related to demographics, emotions, and behavioral characteristics. You will also be video-recorded when you evaluate test samples to see any trends of behaviors across participants. It will take approximately 40 minutes to complete this study. You will also be asked to refrain from smoking, eating, and drinking for 2 hours prior to your evaluation; drinking water is allowed.

Risks and Benefits: All food and beverage samples presented in this study are prepared with commercially available ingredients or products. However, if you have known allergies or intolerances for specific ingredients or foods, please describe them here: _______________________. After completing this study, you will receive a Walmart gift card ($20) as monetary reward.

Voluntary Participation: Your participation in the research is completely voluntary. The voluntary participation, i.e., choosing to participate or not, will have no effect on your relationship with the researchers or the University in any way.

Confidentiality: Your information on identity (e.g., name) will be coded as number (e.g., 1, 2, 3, etc.). The code number will be matched with your responses; that is, your data will be recorded anonymously, except for video recordings. Video recordings will be saved separately from the consent form that includes information on your identity, in both local hard drive and web cloud storage in the Department of Food Science. All information will be kept confidential to the extent allowed by law and University policy. Results from the research will be reported as aggregate data.

Right to Withdraw: You are free to refuse to participate in the research and to withdraw from this study at any time. Your decision to withdraw will bring no negative consequences — no penalty to you.

Informed Consent: I, the undersigned, have read the description, including the purpose of the study, the procedures to be used, the potential risks, the confidentiality, as well as the option to withdraw from the study at any time. Each of these items has been explained to me by the investigator. The investigator has answered all of my questions regarding the study, and I believe I understand what is involved. My signature below indicates that I freely agree to participate in this study and that I have received a copy of this agreement from the investigator. To minimize any potential risks of COVID-19, I will sign on this electronic form by printing my name and describing the date below, instead of signing on the paper form:

____ ________________________

Signature of the participant **Date**

If you have questions or concerns about this study, please contact one of the researchers listed above. For questions or concerns about your rights as a research participant, please contact the University's IRB Coordinator listed as "Administrator" above.

IRB# 2108348008 Approval Date: 08/16/2021