Department of Food and Nutrition
University of Helsinki
Dissertationes Universitatis Helsingiensis 13/2025

INSIGHTS INTO ORAL CHEMESTHETIC PERCEPTION

A FOCUS ON FOOD-RELATED BEHAVIOR

Sulo Roukka

ACADEMIC DISSERTATION
To be presented, with the permission of the Faculty of Agriculture and Forestry of the University of Helsinki, for public examination in lecture hall PIII, Porthania building, City Center Campus of the University of Helsinki, Yliopistonkatu 3, Helsinki Finland, on January 24th, 2025, at 12 noon.

Helsinki 2025

Custos and main supervisor
Professor, Ph.D. Mari Sandell
Department of Food and Nutrition
Faculty of Agriculture and Forestry
University of Helsinki
Finland

Nutrition and Food Research Center
Faculty of Medicine
University of Turku
Finland

Co-supervisor
University Lecturer,
Ph.D.; M.Sc. (Eng.) Laila Seppä
Department of Food and Nutrition
Faculty of Agriculture and Forestry
University of Helsinki
Finland

Preliminary examiners
Associate Professor, Ph.D. Carolina Chaya
Department of Agricultural Economics,
Statistics, and Business Management
Universidad Politécnica de Madrid
Spain

Associate Professor, Ph.D. Sara Spinelli
Department of Agriculture, Food,
Environment, and Forestry
University of Florence
Italy

Opponent
Professor, Ph.D. John E. Hayes
Department of Food Science,
Sensory Evaluation Center
College of Agricultural Sciences
Pennsylvania State University
United States of America

This research was completed under the Doctoral Program in Food Chain and Health at the Department of Food and Nutrition, Faculty of Agriculture and Forestry, University of Helsinki

Front cover illustration by M.Sc. Sebastian Dahlström

Publisher:	University of Helsinki
Series:	Universitatis Helsingiensis 13/2025
	ISBN 978-952-84-0488-0 (print)
	ISBN 978-952-84-0487-3 (online)
	ISSN 2954-2898 (print)
	ISSN 2954-2952 (online)
	Unigrafia Helsinki / PunaMusta, Joensuu 2025

ABSTRACT

Oral chemesthesis is the chemical dimension of somatosensation, which, together with taste and retronasal smell, influence the flavor experience of food. Several different chemical compounds present in food can activate receptor channels specialized for tactile senses that are connected to free nerve fibers. From there, the chemosensory message is transmitted via cranial nerves to the brain, where the perception of chemesthesis is processed.

The created chemesthetic sensations vary and are quality specific. For example, the capsaicin in chili can create a pungent burning sensation, and the menthol contained in mint can activate a cooling sensation. An astringent sensation, i.e., drying of the mouth and constriction of the mucous membranes, can be experienced from red wine that contains polyphenolic compounds such as tannins, or from various metallic salts. Chemesthesis plays an important role in the experience of food. Thus, this study aims to bring new insights about the individual experience of oral-area chemesthesis, the variables that explain the phenomenon, and its connection to food-related behavior and health.

Oral chemesthesis was measured using prototypical compounds (capsaicin, *l*-menthol, and aluminum ammonium sulfate) in liquid samples of different concentrations. The participants (*N*=205) evaluated the intensity of the samples and identified the chemesthetic stimuli in the sensory research laboratory. In addition, participants filled in questionnaires asking information on their background (e.g., age, gender, smoking status, and body mass index) and eating behavior (i.e., consumption and recalled pleasantness of food and beverage items, and dietary habits).

The participants were divided into different sensitivity groups based on quality-specific evaluation results using hierarchical clustering, which was used to identify hyposensitive, semi-sensitive, and hypersensitive individuals. In addition, a chemesthetic sensitivity score was created from the combination of each chemesthetic quality (pungency, cooling, and astringency) that aimed to model a more generalized picture of sensitivity. Results showed that chemesthetic sensitivity was connected with taste sensitivity. Gender and age variables partially explained chemesthetic perception. Women experienced samples containing capsaicin "pungency" more intensely than men. Age was associated with the experience of sensitivity with all chemosensory characteristics. The study showed that chemesthetic sensitivity was connected to food-related behavior, such as consumption and experiencing the pleasantness of certain foods. The perception of chemesthesis was found to be individual, and a quality-specific examination of chemesthesis provided more details about the experience. Food experience is multisensory, and therefore, individual chemesthetic perception should be taken into account in the sustainable product development of foods.

TIIVISTELMÄ

Kemotunto on tuntoaistin kemiallinen ulottuvuus, joka osallistuu yhdessä maku- ja hajuaistin ohella ruoan flavorikokemuksen muodostamiseen. Osa ruoan sisältämistä kemiallisista yhdisteistä pystyy aktivoimaan tuntoaistiin erikoistuneita reseptorikanavia, jotka ovat liitoksissa vapaisiin hermosäikeisiin. Näiden hermosäikeiden avulla kemotuntoviesti siirtyy aivohermojen välityksellä aivojen tuntoaistimusta käsittelevälle alueelle.

Muodostuneet tuntemukset vaihtelevat ja ovat ärsykekohtaisia. Esimerkiksi chilin sisältämä kapsaisiini pystyy muodostamaan suussa pistävän polttavaa tuntemusta ja mintun sisältämä mentoli kykenee aktivoimaan viilentävää tuntemusta. Astringoivuutta, eli suuta kuivattavaa ja limakalvoja supistavaa tunnetta, voidaan kokea esimerkiksi punaviinien sisältämistä polyfenolisista yhdisteistä, kuten tanniineista, tai erilaisista metallisuoloista. Kemotunto on siis tärkeässä roolissa ruoan kokemisessa. Tämän väitöskirjan tavoitteena on tuoda uutta näkemystä suun alueen kemotunnon yksilöllisestä kokemisesta, tarkastella ilmiötä selittävien muuttujien roolia sekä tutkia kemotunnon yhteyttä ruokakäyttäytymiseen ja terveyteen.

Tutkimuksessa mitattiin suun alueen kemotunnon kokemista eri pitoisilla nestemäisillä näytteillä, jotka valmistettiin kemotuntoa aktivoivista prototyyppisistä yhdisteistä (kapsaisiinista, *l*-mentolista, ja alumiiniammoniumsulfaatista). Tutkittavat (N=205) arvioivat näytteiden voimakkuutta ja yrittivät tunnistaa eri kemotunto-ominaisuuksia aistilaboratoriossa. Arvioinnin lisäksi tutkittavilta kysyttiin taustatietoja (mm. ikä, sukupuoli, tupakointistatus ja painoindeksi) ja ruokakäyttäytymiseen (ts. eri ruokien ja juomien käyttöuseutta ja miellyttävyyttä sekä syömistapoja) liittyviä kysymyksiä.

Tutkittavat pystyttiin jakamaan hierarkkisella klusteroinnilla kemotunto-ominaisuuskohtaisiin herkkyysryhmiin, jonka avulla tunnistettiin epäherkät, keskiherkät ja erittäin herkät yksilöt. Lisäksi tutkittujen kemotunto-ominaisuuksien yhdistelmästä rakennettiin kemotuntomittari, jolla mallinnettiin kokonaisvaltaisempaa kemotuntoherkkyyttä. Tuloksista havaittiin, että kemotuntoherkkyyden ja makuherkkyyden välillä oli yhteyksiä. Sukupuoli ja ikä selittivät osittain kemotuntoherkkyyden yksilöllisyyttä. Naiset kokivat kapsaisiininäytteiden polttavuuden herkemmin kuin miehet. Iällä oli yhteys herkkyyden kokemukseen kaikilla kemotunto-ominaisuuksilla. Kemotuntoherkkyys oli myös yhteydessä ruokaan liittyvään käyttäytymiseen, kuten tiettyjen ruokien kulutukseen ja miellyttävyyden kokemiseen. Kemotunnon havaitseminen on yksilöllistä ja ominaisuuskohtainen tarkastelu antaa paremman kuvan kokemuksesta. Ruokakokemus on moniaistista ja siksi kemotunnon yksilöllinen kokeminen tulisi huomioida vastuullisten elintarvikkeiden tuotekehityksessä.

SAMMANDRAG

Kemestes är den kemiska dimensionen av somatosensation, som tillsammans med smak och lukt deltar i att forma matens smakupplevelse. Vissa av de kemiska föreningarna som finns i livsmedel kan aktivera receptorkanaler som specialiserar sig på känsel. De är i sin tur kopplade till fria nervfibrer, genom vilka det kemosensoriska meddelandet överförs via kranialnerver till området som hanterar känseln.

Förnimmelserna som bildas varierar beroende på stimulansen. Till exempel kan kapsaicin som finns i chili skapa en stickande brännande känsla i munnen, och mentolen som finns i mynta kan aktivera en svalkande känsla. En så kallad astringens känsla, då munnen torkar, strävhet, och slemhinnorna drar ihop sig, kan t.ex., upplevas via polyfenoliska föreningar som tanniner som finns i rödvin, eller via olika metallsalter. Kemestes spelar därför en viktig roll i upplevelsen av livsmedel och är syftet med denna studie är att undersöka och ge nya insikter om den individuella upplevelsen av munområdets kemestes, de variabler som förklarar fenomenet och kopplingen till matbeteende och hälsa.

I studien mättes upplevelsen av kemestesen i munområdet med hjälp av vätskeprovuppsättning som innehöll prototypiska föreningar (kapsaicin, *l*-mentol och aluminiumammoniumsulfat) i olika koncentrationer. Deltagarna (N=205) utvärderade intensiteten av proverna och identifierade olika kemestetiska egenskaper i det sensoriska forskningslaboratoriet. Utöver utvärderingen tillfrågades försökspersonerna bakgrundsinformation (t.ex., ålder, kön, rökstatus, och kroppsmasseindex) och frågor relaterade till matbeteende (d.v.s., frekvens av användning och behaglighet av olika livsmedel samt drycker och matvanor). Det var möjligt att dela in försökspersonerna i känslighetsgrupper baserat på egenskaperna i deras kemosensationer genom hierarkisk klusteranalys, som användes för att identifiera hypokänsliga, måttligt känsliga, och hyperkänsliga individer.

Utöver klusteranalysen byggde ett kemestetiskt poängsättningssystem i vilken olika kemestetiska egenskaper kombinerades. Den kemestetiska poängsättningen syftade till att skapa en mer omfattande bild av allmän kemestetisk känslighet. Kemestetisk känslighet var kopplad till smakuppfattningens känslighet. Kön och ålder var variabel som delvis förklarade den kemestetiska uppfattningen. Enligt resultaten var kvinnor mer känsliga än män till hettan i prover som innehöll kapsaicin. Ålder hade en koppling till upplevelsen av känslighet i relation till alla kemosensoriska egenskaper. Studien fann att kemestetiska känslighet också var kopplad till matrelaterat beteende, såsom behagligheten av att uppleva eller konsumera vissa livsmedel. Den kemestetiska känslan förnimmelsen visade sig vara individuell. En undersökning av de kemestetiska egenskaperna ger en bättre helhetsbild av upplevelsen. Matupplevelsen är multisensorisk, och därför bör den individuella upplevelsen av den kemestetiska känslan beaktas i produktutvecklingen av ansvarfulla livsmedel.

ACKNOWLEDGEMENTS

First, I want to thank the Academia. I am grateful to the University of Helsinki, its Doctoral School, the Doctoral Program in Food Chain and Health, the Faculty of Agriculture and Forestry and the Department of Food and Nutrition, the University of Turku, Faculty of Medicine and Nutrition and Food Research Center (formerly Functional Foods Forum), the Finnish Food Research Foundation (Elintarvikkeiden Tutkimussäätiö) and the Research Council of Finland (Suomen Akatemia) for funding this doctoral research and making this amazing doctoral research journey possible.

Thank you, my supervisors Professor, Ph.D. Mari Sandell and University Lecturer Ph.D.; M.Sc. (Eng.) Laila Seppä for helping me to find my inner doctor. I am forever grateful for your excellent guidance and help throughout this doctoral research project. I thank my co-authors Ph.D. Sari Puputti, Ph.D. Heikki Aisala, and Ph.D. Ulla Hoppu for their great contribution to this research project and advice. I also thank all the Senses and Food Finland research team members that have been part of the FoodTaste Finland Research Program for their input. I also thank of all the participants who attended the sensory study at the University of Turku.

I thank my Thesis Committee members Professor, Ph.D. Mari Niva, Docent, Ph.D. Sari Mustonen, and Ph.D. Terhi Pohjanheimo for mentoring and monitoring the progress of this doctoral research project.

I am very grateful for the reviewers of this doctoral thesis, Associate Professor, Ph.D. Carolina Chaya and Associate Professor, Ph.D. Sara Spinelli for their valuable and constructive comments that help in completing this manuscript. I also thank University Lecturer, Ph.D. Alyce Whipp who agreed to revise the English language of this doctoral thesis.

I thank Professor, Ph.D. John E. Hayes for agreeing to act as my opponent, I am looking forward to defending this thesis.

I also want to thank my dear colleagues Ph.D. Maija Greis and Doctoral researcher, M.Sc. Fabio Tuccillo, it has been fun investigating the secrets to the multisensory experiences with you. I particularly would like to thank Maija for her thoughtful comments for this dissertation and for setting a high bar for acknowledgement wording in academic writing.

Mina kärä vänner M.Sc. Sebastian and B.A. Rose-Marie Dahlström, jag måste tacka er för den grafiska och språkliga hjälpen! I also thank B.Sc. Troy Faithfull for his comments and assistance with the language. A very big thank you goes to my dear friend Pertti Tuohino, who helped me with my writing in the begging face of this project.

I thank sensory scientists Docent, Ph.D. Antti Knaapila, Docent, Ph.D. Oskar Laaksonen, and M.Sc. Jutta Varis for our great discussions. I would also like to thank my friends Ph.D. Saara Sammalisto, Doctoral researcher, M.Sc. Iida Loivamaa, M.Sc. Isa Stucki, B.Eng. Tuulia Karvinen, and all our other University of Helsinki staff members.

I want to thank my parents Jussi and Päivi Roukka for their loving support, and for giving me life perspective. I also thank my beautiful sisters Elli, Elsa, and Erja and their families for their support and love. I warmly thank Kaisa Roukka, Tiina & Juha Jahkola, Minna Roukka, Taru & Tane Autio-Kanto, Pyry & Aino Jahkola, Lauri & Sanna Jahkola, Tuuli & Joni Hyvönen, Mikaela & Juuso Naumanen, Patrick Dahlberg and all my relatives with their families for their support. In addition, I also thank my godparents Sirkka-Liisa "Samu", Kimmo, Matti, and Auli.

I also wish to thank ALL of my friends, but most importantly, I thank my best friend and husband Juha Markkanen for his love, help, and patience. Last but not least, our beloved cats Suri and Pirjo. And never forgetting our cats Untamo and Kaapo, sending love somewhere over the rainbow <3.

You all have made my doctoral researcher journey a memorable experience! And thank you, the reader of this dissertation, for your interests regarding sensory science and chemesthesis!

Punkalaidun, December 2024

Sulo Roukka

LIST OF ORIGINAL PUBLICATIONS

I. **Roukka, S.**, Puputti, S., Aisala, H., Hoppu, U., Seppä, L., & Sandell, MA. The Individual Differences in the Perception of Oral Chemesthesis Are Linked to Taste Sensitivity. *Foods*. 2021; *10*(11):2730. doi:10.3390/foods10112730

II. **Roukka, S.**, Puputti, S., Aisala, H., Hoppu, U., Seppä, L., & Sandell, MA. Factors Explaining Individual Differences in the Oral Perception of Capsaicin, *l*-Menthol, and Aluminum ammonium sulfate. *Clinical and Translational Science*. 2023; *00*: 1-13. doi:10.1111/cts.13587

III. **Roukka, S.**, Puputti, S., Hoppu, U., Seppä, L., & Sandell, MA. Role of Oral Chemesthetic Sensitivity in the Consumption and Recalled Pleasantness of Foods and Beverages. Manuscript

These publications are referred to in the text by their Roman numerals. These articles are reproduced with the kind permission of their copyright holders.

RESEARCH INPUT AND AUTHORSHIP

I. Sulo Roukka was the responsible author for drafting and writing the manuscript and analyzed the data. Authors Ph.D. Sari Puputti, Ph.D. Heikki Aisala, Ph.D. Ulla Hoppu, Ph.D. Laila Seppä, and Professor Mari Sandell contributed to the manuscript writing process by reviewing and editing. Professor Mari Sandell, Ph.D. Sari Puputti, Ph.D. Heikki Aisala, and Ph.D. Ulla Hoppu designed the research. In addition, Ph.D. Sari Puputti, Ph.D. Heikki Aisala, and Professor Mari Sandell performed the research. Sulo Roukka, Ph.D. Sari Puputti, Ph.D. Heikki Aisala, and Professor Mari Sandell contributed new analytical tools. This research was supervised by Professor Mari Sandell and Ph.D. Laila Seppä. Professor Mari Sandell was the corresponding author.

II. Sulo Roukka was the responsible author for drafting and writing the manuscript and analyzed the data. Authors Ph.D. Sari Puputti, Ph.D. Heikki Aisala, Ph.D. Ulla Hoppu, Ph.D. Laila Seppä, and Professor Mari Sandell contributed to the manuscript writing process by reviewing and editing. Professor Mari Sandell, Ph.D. Sari Puputti, Ph.D. Heikki Aisala, and Ph.D. Ulla Hoppu designed the research. In addition, Ph.D. Sari Puputti, Ph.D. Heikki Aisala, and Professor Mari Sandell performed the research. Sulo Roukka, Ph.D. Sari Puputti, Ph.D. Heikki Aisala, and Professor Mari Sandell contributed new analytical tools. This research was supervised by Professor Mari Sandell and Ph.D. Laila Seppä. Sulo Roukka and Professor Mari Sandell shared the corresponding authorship.

III. Sulo Roukka was the responsible author for drafting and writing the manuscript and analyzed the data. Authors Ph.D. Sari Puputti, Ph.D. Ulla Hoppu, Ph.D. Laila Seppä, and Professor Mari Sandell contributed to the manuscript writing process by reviewing and editing. Professor Mari Sandell, Ph.D. Sari Puputti, Ph.D. Heikki Aisala, and Ph.D. Ulla Hoppu designed the research. In addition, Ph.D. Sari Puputti, Ph.D. Heikki Aisala, and Professor Mari Sandell performed the research. Sulo Roukka, Ph.D. Sari Puputti, Ph.D. Heikki Aisala, and Professor Mari Sandell contributed new analytical tools. This research was supervised by Professor Mari Sandell and Ph.D. Laila Seppä. Sulo Roukka and Professor Mari Sandell shared the corresponding authorship.

ABBREVIATIONS

ANOVA	Analysis of variance
BMI	Body mass index
CATA	Check-All-That-Apply
CAS	Chemical Abstracts Service
COVID-19	Pandemic of coronavirus disease, an infectious disease caused by the SARS-CoV-2 virus, impacting the functional properties of chemical senses.
CSS	Chemesthetic sensitivity score
DPW	Doses per week
EC	European Commission
EFSA	European Food Safety Authority
EU	European Union
F&B	Food and beverage
GDPR	General data protection regulation
HSD	Honestly significant difference (Tukey's *post-hoc* test)
ISO	International Organization for Standardization
LSD	Least significant difference (Fisher's *post-hoc* test)
MANOVA	Multivariate analysis of variance
MNLR	Multinomial logistic regression
N	Total number of observations or population size
n	Sample size
ns	Non-significant, $p \geq 0.05$
OR	Odds ratio (a measure that indicate the odds, direction, and strength of outcome between predictor and response variables)
p	Probability of rejecting the null hypothesis when it is true, that is, risk associated with Type I errors.
PCA	Principal component analysis
PLS	Partial least square regression
RATA	Rate-All-That-Apply
SFS	Finnish Standards Association
S+H	Combined semi-sensitive and hypersensitive group
sig	Significant "$p<0.05$"
TRP	Transient receptor potential somatosensory receptors' cation channels (e.g., TRPV1 "vanilloid 1", TRPA1 "ankyrin 1", and TRPM8 "melastatin 8")

Table 1. Abbreviations used in different publications for the chemesthetic sensitivity measurements throughout this doctoral research.

Chemesthetic dimension	Prototypic compound	Article I	Article II	Manuscript III	Dissertation
Pungency	Capsaicin	Pungency Chemesthetic Sensitivity Group: P-CSG	Capsaicin Sensitivity Group: CSG	Capsaicin Sensitivity Group: CSG	Pungency (Capsaicin) Sensitivity Group: CSG
Coolness	*l*-Menthol	Cooling Chemesthetic Sensitivity Group: C-CSG	*l*-Menthol Sensitivity Group: MSG	*l*-Menthol Sensitivity Group: MSG	Cooling (*l*-Menthol) Sensitivity Group: MSG
Astringency	Aluminum ammonium sulfate	Astringency Chemesthetic Sensitivity Group: A-CSG	Aluminum ammonium sulfate Sensitivity Group: ASG	Aluminum ammonium sulfate Sensitivity Group: ASG	Astringency (Aluminum ammonium sulfate) Sensitivity Group: ASG
Combined (Pungency, Coolness, and Astringency)			Combined Oral Chemesthetic Sensitivity Group: COCSG	Combined Oral Chemesthetic Sensitivity Group: COCSG	Combined Oral Chemesthetic Sensitivity Group: COCSG

DEFINITIONS

Ageusia	Clinical term for loss of taste
Alexithymia	Emotional blindness linked to challenges in expressing and recognizing one's emotions
Anosmia	Clinical term for loss of smell
Chemesthesis	Chemically activated somatosensory (tactile) sensation
Flavor	Multisensory perception of three chemical senses: taste, retronasal smell, and chemesthesis
Food neophobia	Fear or strong avoidance of novel foods
FoodTaste Finland	Research Program: Human taste sensitivity and multisensory perception of food
Irritant	In this context, chemesthetic compounds that cause pungent irritation or inflammation when contacting the body
Neuropathy	Clinical term for dysfunction and pathological changes in the peripheral nervous system
Somatosensation	A physiological process including a collection of tactile sensations such as touch pressure, vibration, balance, positioning, movement, pain, and temperature, which are often activated by physical stimuli but also including the chemical dimension "chemesthesis"
Tastant	Chemical compound that activate taste perception

CONTENTS

ABSTRACT iii
TIIVISTELMÄ iv
SAMMANDRAG v
ACKNOWLEDGEMENTS vi
LIST OF ORIGINAL PUBLICATIONS viii
RESEARCH INPUT AND AUTHORSHIP ix
ABBREVIATIONS x
DEFINITIONS xii

1. INTRODUCTION ... 1
2. REVIEW OF THE LITERATURE ... 4
2.1. Oral chemesthetic perception ... 4
2.2. Examples of chemesthetic compounds ... 5
2.2.1. Pungency of capsaicin ... 6
2.2.2. Coolness of *l*-menthol ... 8
2.2.3. Astringency of aluminum ammonium sulfate ... 9
2.2.4. Other oral chemesthesis dimensions ... 10
2.3. Factors contributing to oral chemesthetic perception ... 10
2.3.1. Oral physiology ... 10
2.3.2. Food-related factors ... 12
2.3.3. Age ... 13
2.3.4. Gender ... 13
2.3.5. Health-related factors ... 13
2.3.6. Personality traits ... 14
2.4. Safety challenges of chemesthetic compounds ... 16
3. AIMS OF THE STUDY ... 17
4. MATERIAL AND METHODS ... 18
4.1. Participants ... 18
4.2. Chemesthetic samples ... 20
4.3. Sensory evaluation procedure ... 21
4.4. Questionnaires for background factors and food-related behavior ... 21
4.5. Data processing methods ... 22

4.5.1. Article I ... 22
4.5.2. Article II ... 23
4.5.3. Manuscript III ... 23
4.5.4. Dietary habits ... 24
4.6. Ethical aspects ... 24
5. RESULTS ... 25
5.1. Individuality of chemesthetic sensitivity and connections to taste sensitivity (I) ... 25
5.1.1. Quality-specific chemesthetic sensitivity groups ... 25
5.1.2. Combined oral chemesthetic sensitivity ... 27
5.1.3. Associations between chemesthesis and taste ... 28
5.2. Factors explaining individuality of chemesthetic perception (II) ... 29
5.2.1. Recognition of chemesthesis ... 29
5.2.2. Predictors for sensitivity ... 31
5.3. Connections between chemesthetic sensitivity and food-related behavior (III) ... 32
5.3.1. Sensitivity connections to consumption and recalled pleasantness ... 32
5.3.2. Multidimensional interactions ... 32
5.4. Chemesthetic sensitivity and dietary habits ... 33
5.4.1. Associations between sensitivity and habits ... 34
5.4.2. Impact of sensitivity on habits ... 36
Pungency – Cooling – Astringency – Combined
6. DISCUSSION ... 43
6.1. Chemesthetic perception varies and is connected to taste ... 43
6.2. Role of personal explanatory factors in chemesthetic perception ... 44
6.3. Chemesthesis is a part of food-related behavior ... 45
6.4. Strengths and limitations ... 47
6.5. Future directions ... 48
7. CONCLUSIONS ... 50
REFERENCES ... 51
APPENDIX 1 ... 66
APPENDIX 2 ... 67

1. INTRODUCTION

Food experience is multisensory, involving co-operation of physical and chemical senses. In general, food and beverages (F&B) are filled with compounds that can stimulate the chemosensory system including taste, smell, and chemically activated somatosensory sensation (**Figure 1**) namely chemesthesis, where "*chem*" is pertaining to chemical and "*esthesis*" is the ability to perceive or feel (Pringle, 2016). These chemical sensations are fundamental components of flavor perception and influence the decisions about what foods to eat and consume (Lawless and Heymann 2010; Hayes 2020). For instance, a chili that is often used as a spice can create a pungent sensation (Jordt and Julius 2002), and additives such as artificial sweeteners may trigger irritating sensations (Wierenga et al. 2020). In addition, fermented foods may have chemesthetic properties such as pungency (Loss and Bouzari 2016).

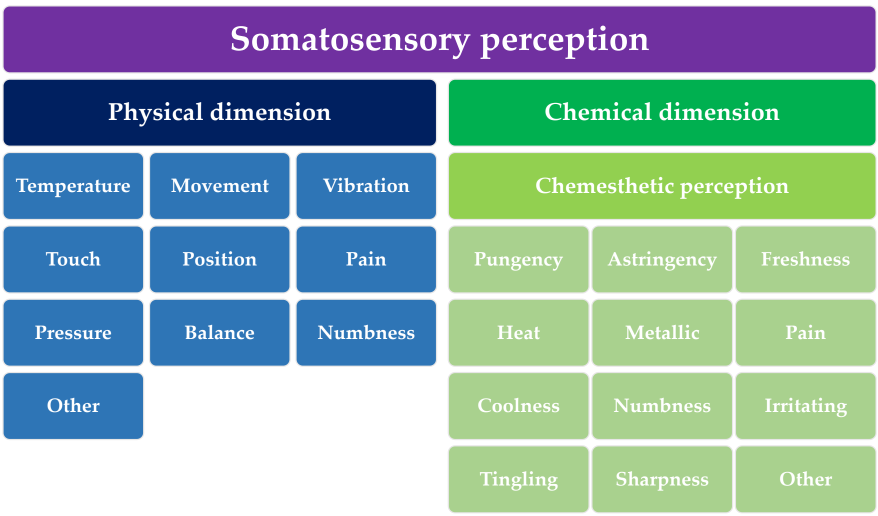


Figure 1. A demonstration of the somatosensory system with some of the main physical and chemical dimensions based on Ager et al. (2020) and Filiou et al. (2015). The chemical dimension is known as chemesthesis. Both somatic dimensions utilize somatosensory receptors.

The perception of flavor is perceived via oral and retronasal pathways and is very complex (Lawless and Heymann 2010). In the field of food science, there is a lack of large-scale studies with a focus on the relationship between individual variabilities in different sensory dimensions like chemesthesis (Piochi et al. 2021). Hence, individuality in oral chemesthetic perception must be explored more to obtain a consensus on its role in food-related behavior (Dalton and Byrnes 2016).

A variety of plants can produce irritating compounds that activate chemesthetic perception, giving them protection against mammals and pests (Haley and McDonald

2016). For example, chilies (Lat. *Capsicum*) produce pungent compounds that belong in the family of capsaicinoids (Thiele et al. 2008). Of these, capsaicin is the most dominant and well-studied pungent irritant (National Center for Biotechnology Information 2024a). Another example is mint (Lat. *Mentha*), which produces a compound named *l*-menthol that can commonly activate the cooling sensation (National Center for Biotechnology Information 2024b). Apart from these thermal-related sensations, a multidimensional sensation of astringency (mouth puckering and drying sensation) is often perceived from fruits and berries that contain polyphenolic or other astringent compounds (Laaksonen 2011).

Chemesthetic compounds can also activate sensations other than chemesthesis. Capsaicin is known to activate taste (Green & Hayes, 2003; Slack, 2016). Thus, chemesthesis can be misunderstood as a part of taste sensation. In addition, volatile chemesthetic compounds can activate retronasal smell and nasal-chemesthesis (Saunder and Silver 2016). This indicates that chemosensory linkage is compound specific. According to Risso et al. (2020), the evolutionary purpose of chemesthesis is similar to bitterness. The general functions of chemesthesis help to avoid and prevent ingestion of potentially harmful or toxic substances.

Chemical senses are part of chemically sensitive defense mechanisms that activate our immune system and warn us against dangerous biological and chemical agents in the environment (Green, 2012). Thus, chemesthetic compounds can activate special receptor channels, sending sensory signals that help avoid inhalation, ingestion, or absorption of potentially hazardous substances. Defensive expulsive reflexes and responses include sneezing, coughing, sweating, lacrimation, and salivation that can be triggered due to high levels of pungent compounds (Green, 2012; Prescott & Stevenson, 1995). Regarding oral area chemesthesis, the chemosensory information of chemesthetic compounds is primarily conveyed via cranial nerves, such as the trigeminal nerve, into the somatosensory cortex area of the brain, where the perception is further processed (Lundström et al. 2011; Saunder and Silver 2016).

The functional mechanisms related to chemesthesis have been studied in the medical field. During the COVID-19 pandemic, interest in chemosensory impairments increased regarding functions of chemical senses (Parma et al. 2020; Risso et al. 2020; Cecchetto et al. 2021), and in 2021, the Nobel Prize in Physiology or Medicine was awarded to David Julius and Ardem Patapoutian for their discoveries of receptors responsible for temperature and touch (The Nobel Assembly at Karolinska Institutet

2021). The same receptors are responsible for chemesthetic perception. Although the molecular and neural mechanisms of chemesthesis have been studied in the medical field, the influence of chemesthetic perception on food choices and preferences requires further exploration.

Food culture varies globally between countries. Different cultural and environmental patterns can impact the intake of food containing chemesthetic ingredients (Mattes and Ludy 2016). For example, the consumption of pungent spices (e.g., black pepper, garlic, ginger, and onion) is high in many Asian countries, and Mexico's food culture is rich in chili usage. In comparison, Mattes & Ludy (2016) state that Nordic countries (e.g., Finland and Norway), have low consumption of pungent spices. The most recent Nordic nutrition recommendations highlight the importance of a plant-based diet and the need to increase vegetable, fruit, and berry consumption (Blomhoff et al. 2023). Interestingly, some plant-based materials, such as fava bean used in product development targeting healthier and more sustainable food solutions, present a challenge due to their high and unpleasant astringent properties (Tuccillo et al. 2024).

An unhealthy diet is one of the leading causes of cardiovascular diseases, diabetes, and cancer (World Health Organization 2023). Understanding chemosensory perception can help with designing preventative solutions against obesity and poor nutrition (Spinelli and Monteleone 2021). As an example, taste impairments can cause discomfort, which can lead to appetite loss, and changes in eating habits (Risso et al. 2020). Consumption of pungent spices, such as chili, cinnamon, and ginger, has been suggested to be linked with health benefits e.g., antimicrobial protection, appetite hormones, body temperature regulation, energy intake and expenditure, and substrate oxidation (Mattes and Ludy 2016). However, some of the chemesthetic ingredients, such as pungent ethanol, can be carcinogenic and have a negative impact on health (Prescott and Swain-Campbell 2000; Rumgay et al. 2021).

This doctoral dissertation aims to provide new insights into oral chemesthetic perception among adult participants. Research included a chemesthesis sensory study and food-related behavior questionnaire results with a special focus on the consumption and recalled pleasantness of F&B-items typical for Nordic food culture and eating habits. A novel model for chemesthetic sensitivity was created, and connections between chemesthesis and taste (Puputti et al. 2018) were explored with the same study participants.

2. REVIEW OF THE LITERATURE

In this review, the fundamentals of oral area chemesthetic perception regarding sensory food science are introduced to you, the readers of this dissertation.

2.1. Oral chemesthetic perception

The somatosensory system has functional properties beyond physical stimuli. Certain chemicals are capable of creating a variety of tactile sensations, which together are defined as chemesthesis. For instance, the pungent sensation of capsaicin that is a burning compound found in chili peppers, the coolness of menthol found in mint, the astringency (i.e., mouth drying, puckering, and shrinking sensation) of phenolic compounds (e.g., tannic acid) found in berries, metallic sensation of artificial sweeteners (e.g., aspartame), and the tingling of carbonated (carbonic acid) beverages are all a part of the diverse family of chemesthesis (Green 1996; Riera et al. 2007; Laaksonen 2011; Hoppu et al. 2016; Roukka et al. 2021). Many chemesthetic compounds are present in nature. For example, some plants such as chili produce irritating compounds against pests and mammals (Slack 2016; Haley and McDonald 2016).

Chemesthetic compounds directly affect somatosensory receptors attached to the nerve endings of the peripheral nervous system responsible for the tactile sensations of temperature, touch, pressure, and pain (Simons and Carstens 2008; Lundström et al. 2011; Roukka et al. 2021). According to the standard terminology related to the sensory evaluation of materials and products by American Society for Testing and Materials (ASTM-WK44511: E253-21, 2014), chemesthesis is determined as a sensory sensitivity to direct chemical stimulation of somatosensory receptors in the skin and mucous membranes covering the human body (Simons and Carstens 2008; Lundström et al. 2011; Roukka et al. 2021). Despite the diversity of chemesthesis, sensitivity throughout these areas is not uniform (Green, 1996).

Sensory signals of chemesthetic sensations are carried by the trigeminal (*cranial nerve* V), glossopharyngeal (*cranial nerve* IX), and vagus (*cranial nerve* X) nerves (Lundström et al. 2011; Slack 2016). The *trigeminal nerve* is the principal somatosensory nerve innervating oral, nasal, and ophthalmic areas, and is primarily associated with oral chemesthetic perception. Different physical defensive reactions such as sneezing, sweating, saliva production, and tears can occur after exposure to chemesthetic compounds (Green, 2012; Törnwall, 2013). Generally, chemesthesis includes a wide array of somatosensations, which are processed in areas of the brain other than where taste and smell are. The sensory information of chemesthetic compounds is conveyed via cranial nerves in the somatosensory cortex area of the brain, where the perception is further processed (Lundström et al. 2011). A functional magnetic resonance imaging (fMRI) study (*N*=24) suggested that three brain regions (lobule IX of the cerebellar hemisphere, right dorsolateral superior frontal gyrus, and left middle temporal gyrus) play a major role in the discrimination and cerebral response to two prototypic oral chemesthesis characteristics: pungency (capsaicin) and astringency (tannic acid) (Zhu et al. 2023b). Furthermore, the chemesthesis is suggested to integrate with flavor perception in the orbitofrontal cortex area of the brain (Carstens 2016).

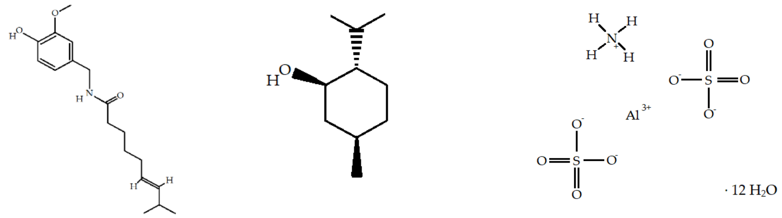
The mouth and nose are covered with mucous membranes filled with exposed somatosensory receptors (Klein 2019). This is why some individuals might misconceive chemesthesis as a part of the taste or smell sensation. An earlier study by Green et al. (2005) indicated that responsiveness to oral chemesthetic (capsaicin and *l*-menthol) stimulation cannot be reliably predicted from the responsiveness to taste stimulation (sweet, sour, salty, and bitter). However, salts and acids are able to produce chemesthetic sensation as well as taste (Green, 1996). Thus, compounds that activate both chemesthesis and taste or smell may be the reason for the confusion between sensations.

According to Ward (2016), the phenomena of sensitization (sensation increases in intensity) and desensitization (sensation decreases in intensity) impact the measurement of chemesthetic perception. Interestingly, some ingredients can interact with chemesthesis by enhancing or inhibiting the sensation (Carstens, 2016; Green, 1996; Hayes, 2016). For example, sucrose can reduce capsaicin-induced oral burning (Carstens 2016). Enhancing and inhibiting interactions are, however, compound and ingredient dependent.

2.2. Examples of chemesthetic compounds

Different chemical compounds can activate oral chemesthetic sensations. The perceived sensation is highly dependent on a compound's structure and is altered by concentration level. Chemesthetic compounds are specific somatosensory receptor agonists (Filiou et al. 2015). This section briefly reviews chemesthetic compounds (**Figure 2**) related to this doctoral research.

A) **B)** **C)**



Capsaicin	*l*-Menthol	Aluminum ammonium sulfate
CAS: 404-86-4	CAS: 2216-51-5	CAS: 7784-26-1
$C_{18}H_{27}NO_3$	$C_{10}H_{20}O$	$AlNH_4(SO_4)^2 \cdot 12H_2O$
305.4 g/mol	156.3 g/mol	453.3 g/mol

Figure 2. Molecular structure and characteristics of chemesthetic chemicals: capsaicin (A), *l*-menthol (B), and aluminum ammonium sulfate (C).

2.2.1. Pungency of capsaicin

Capsaicin (trans-8-methyl-N-vanillyl-6-nonenamide), visualized in **Figure 2A**, is a member of the capsaicinoid family, which are naturally-occurring pungent botanical irritants and secondary metabolites of all plants from the *Capsicum* genus, including chili pepper (National Center for Biotechnology Information 2024a). History tells us that capsaicin was first isolated in 1846, and the structure determined in 1919 (Sawynok 2005; Hayman and Kam 2008). Moreover, it is a phenolic, lipophilic, and odorless compound that is insoluble in cold water. Capsaicin is the most encountered pungent compound in foods (Hayman and Kam 2008; Hayes 2016). Additionally, it can be perceived or described as burning, a warmth, hot, tingling, biting, numbing, and itching (Lawless and Stevens 1988; Hayes 2016; Zhu et al. 2023a). Apart from the pungent sensation, capsaicin is capable of stimulating a bitter taste (Green, 2003; Nolden et al., 2016). In high concentrations or for a long period of time, capsaicin has neurotoxic properties causing progressive degeneration to the somatosensory nerves and can trigger pain (Simone et al. 1998; Ilie et al. 2019; National Center for Biotechnology Information 2024a). Thus, Regulation (EC) No 1334/2008 of the European Parliament and the Council of 16 December 2008 on flavorings and certain food ingredients with flavoring properties for use in and on foods, forbids the direct usage of capsaicin in foods.

Capsaicin is the most classic TRPV1 (Transient Receptor Potential Vanilloid member 1) cation channel agonist in all mammals, including humans, that has a role in pain perception (Caterina et al. 1997; Zhang et al. 2023a). In addition, K_{2P} (two-pore domain potassium) channels have physiological roles in the perception of pungent substances (Beltrán et al. 2013). These receptor channels are connected to free nerve endings of sensory neurons that convey the chemosensory information to the cortex.

The total amount of capsaicinoids, including capsaicin, varies among different chili species and areas within the fruits (Fattori et al. 2016). The highest amount of capsaicin has been reported to be in placental tissue, that is the part where the chili seeds are attached (Thiele et al. 2008). Burning in the oral area is commonly detectable at a concentration of 1 part per 100,000 (National Center for Biotechnology Information 2024a). The hotness of the chilies has been popularly modelled with Scoville test that generates Scoville Heat Units as an estimate of perceived intensity (Scoville 1912). However, more advanced chromatographic methods such as MISER HPLC-ESIMS has been used to analyze the capsaicin in chili peppers and hot sauces (Welch et al. 2014).

Capsaicin and other pungent irritants presumably protect seed germination from threats such as pests, rodents, and other mammals (Haley and McDonald 2016; Hayes 2016). Evolutionarily, avians are exceptionally unable to perceive the noxiously pungent sensation of capsaicin since their TRPV1 cation channels fail to be activated by capsaicin, making them favored vectors for seed dispersal (Jordt and Julius 2002; Tewksbury et al. 2008; Clark et al. 2015).

Capsaicin is a nonvolatile compound (National Center for Biotechnology Information 2024a). This is why while eating chilies, capsaicin remains mainly in the oral cavity area, and it is unlikely to stimulate the nasal region during eating. In comparison, other pungent compounds that are volatile, such as allyl isothiocyanate (found in wasabi, horseradish, and mustard), can stimulate retronasal chemesthesis (Corrales et al. 2014).

Nolden et al. (2024) revealed that repeated low-dose exposure to capsaicin can systematically induce desensitization. In contrast, earlier research underlines that both an increase and decrease in sensations occur in response to repeated short term stimulation of capsaicin (Prescott and Swain-Campbell 2000). This may indicate greater individual variability in response patterns that time course largely determines between irritant response variation.

An earlier sensory study (*N*=20) by Lawless & Stevens (1988) indicated that the oral responsiveness in capsaicin-induced irritation varied and that perceived intensity grew over time. Participants perceived capsaicin samples (7 mm disks of Whatman Qualitative Grade 1 filter paper; 2.5 μg capsaicin) and selected sensations in the following categories: taste (sweet, sour, salty, bitter, and metallic), temperature (burning, very hot, hot, very warm, and warm), tactile (stinging, prickling, biting, itching, piercing, and other), and flavor (peppery, spicy, tangy, astringent, flavorful, and other). As a result, capsaicin created intense responses from the lips and posterior tongue.

Capsaicin can improve flavor by adding a hot and spicy pungent kick. Hunter et al. (2023) and (Wang et al. 2022) found that capsaicin can increase the intensity of saltiness in low NaCl concentrations. Hunter et al. (2023) highlighted that capsaicin's effect on liking differed by the food type. Spicy foods made from chili contain capsaicin. The consumption of spicy food is associated with a lower sensitivity to capsaicin (Su et al. 2022). Additionally, frequent chili pepper consumers have a lower burn intensity and higher liking than infrequent consumers (Lyu et al. 2021). Sensory studies have revealed that capsaicin is connected to reducing sweetness in foods (soup and flavored mixes), yet, does not impact saltiness or sourness (Prescott 1995; Cayeux et al. 2023).

Some F&B-items can obtain properties that contribute to the reduction of oral burning. The fat and protein structure of foods, along with temperature, has been proven to be associated with reductions in the capsaicin oral burn (Gaiser and Hayes 2024). Since capsaicin is a hydrophobic and fat-soluble compound (Hayman and Kam 2008), a water rinse in the mouth will spread the molecules around and activate other available TRPV1 cation channels, stimulating the pungent sensation. Gaiser & Hayes (2023) revealed that high protein ultra-filtered cow's milk was the most efficacious rinse compared to water and other dairy milks or plant-based alternatives. In addition, Nolden et al. (2019) suggested that milk is the best choice to mitigate burning, suggesting the presence of proteins as being more relevant than the lipid content.

2.2.2. Coolness of *l*-menthol

l-Menthol (5-methyl-2-(1-methylethyl)cyclohexanol), visualized in **Figure 2B**, is a covalent organic cooling compound and a cyclic monoterpene found in mint (McKemy et al. 2002; Roukka et al. 2021; Roukka et al. 2023; National Center for Biotechnology Information 2024b). It is an agonist for TRPM8 (Transient Receptor Potential subfamily Melastatin, member 8) cation channels that can be activated by cold temperatures and by other cooling agents (McKemy et al. 2002; Peier et al. 2002; Zhang et al. 2023a). Furthermore, *l*-menthol has poor solubility in water and its volatile properties activate the peppermint odor (National Center for Biotechnology Information 2024b).

While *l*-menthol is known to activate a cooling sensation (Pringle 2016), it can also activate the sensations of pungency and pain in high concentrations in body areas where TRPM8 cation channels are linked to free-nerve endings (Prescott and Stevenson 1995; Peier et al. 2002; Pringle 2016). The intensity and duration of the cooling and burning sensation of menthol (isomer types *l* and *d*) are dependent upon the concentration (Gwartney and Heymann 1995). Moreover, *l*-menthol has a more intense and long lasting pungent burning sensation compared to *d*-menthol.

These kinds of chemical cooling agents are often present in fresh tasting gums and confectionary products (Pellegrino and Luckett 2019). Coolness is found to be a key driver of a refreshing sensation, and it is known to enhance the freshness of beverages (Labbe et al. 2009; Labbe et al. 2011). A sensory study showed that *l*-menthol can reduce the sweetness and sourness in lemon-flavored yogurt samples (Koskinen et al. 2003; Cayeux et al. 2023). Apart from foods, *l*-menthol is used in unhealthy products such as cigarettes, due to its sensory properties that improve the flavor experience masking the nicotine flavor (Chéruel et al. 2017; Levy et al. 2023).

2.2.3. Astringency of aluminum ammonium sulfate

Aluminum ammonium sulfate ($AlNH_4(SO_4)^2 \cdot 12H_2O$), visualized in **Figure 2C**, is a metallic salt and non-volatile compound that can activate strong astringency in the oral area (National Center for Biotechnology Information 2024c). Aluminum ammonium sulfate is freely soluble in glycerol but practically insoluble in alcohol, while 1 g dissolves in 20 mL of cold water. It can be used in an assessors screening test of ageusia and anosmia (SFS: ISO 8586:2012). As an additive, aluminum ammonium sulfate has an acceptable daily intake limit of 0.14 mg/kg/day, and it can only be used in candied cherries in Europe (Finnish Food Authority 2024a).

Astringency is a complex group of somatosensations (Lee and Lawless 1991; Dinnella et al. 2011). Different types of astringent compounds, such as metallic salts and phenolic compounds, can vary in molecular mechanisms affecting their binding with oral and salivary proteins (Peleg et al. 1998). According to Laaksonen (2011), the astringency sensation can be influenced by bitterness (phenolic compounds), metallic sensation (cations), sweetness (masking by sugars), fat perception (masking by fats), texture (friction particle size), sourness (pH and acids), and possibly by umami (mouth-drying). The response to aluminum ammonium sulfate differs from the response to phenolic compound-elicited astringency (Peleg et al. 1998). In addition, astringency (aluminum ammonium sulfate) is reduced by the addition of acids (citric acids, lactic acid, and hydrochloric acid).

TRPA1 and TRPV1 channels have been associated with the astringency sensitivity of green tea (Kurogi et al. 2015). These same channels have been linked with the sensation of oral astringency in mammals (Takahashi et al. 2021). However, the molecular mechanism of astringency is still unclear since the astringency sensation can vary by compound. Nevertheless, a higher responsiveness to astringency (aluminum ammonium sulfate) has been noted to be associated with a lower intake of alcoholic beverages (Thibodeau et al. 2017). In contrast, the responsiveness to the astringency of tannic acid is associated with a lower intake of phenol-rich foods such as vegetables, berries, and fruits (Dinnella et al. 2011).

2.2.4. Other oral chemesthesis dimensions

In addition to pungency, coolness, and astringency, other chemesthesis dimensions also impact the oral area. These include sensations such as the tingle sensation of carbonation (H_2CO_3), numbing of Szechuan pepper (α-hydroxy sanshool) (Simons 2016), and metallic sensation of metallic salts (Laaksonen 2011). Some compounds like capsaicin and *l*-menthol can create the sensation of pain, especially at extremely high concentrations (Caterina et al. 1997; Peier et al. 2002; Dalton and Byrnes 2016; Pringle 2016). Pain is a complex sensation that is experienced by multiple networks in the brain using both limbic and somatosensory systems (Dinakar and Stillman 2016).

2.3. Factors contributing to oral chemesthetic perception

Certain factors influence oral chemesthetic perception. These include oral physiology, food-related factors, age, gender, health-related factors, and personality traits. Here some of those dimensions are introduced.

2.3.1. Oral physiology

The human mouth has a strong role in eating and drinking F&B. The oral region consists of multiple subsites and parts (**Figure 3**), each involved in the eating process. These include the lips, teeth, palate, tongue, floor of the mouth, gingiva (gums), uvula, retromolar trigone, tonsils, gingivobuccal sulcus, palate (hard, soft), and salivary glands (Famuyide et al. 2022). The mouth is covered with mucous membranes, microbes, and saliva containing vital substances for digestion by moistening foods, enzymatic reactions, antimicrobial, and other protective mechanisms (Alhajj and Babos 2023). Stratifying squamous epithelial layers, including keratinized, non-keratinized, and specialized (mixture of keratinized and non-keratinized) cover the oral cavity (Finger and Simon 2000; Saunder and Silver 2016). Most of the chemesthetic stimuli appear to be lipophilic and diffuse through the epithelial cells' membranes, reaching the free nerve endings below the tight junctions binding the cells of the epithelial layers together.

The saliva structure and properties can influence chemesthetic perception. For instance, the individual variability of salivary proteins such as proline-rich proteins and the flow rate impact how intense the astringency sensation will be (Jöbstl et al. 2004; Bajec and Pickering 2008; Dinnella et al. 2009; Laaksonen 2011; Törnwall 2013). In addition, lower pH, higher temperature, and lower viscosity increase the perceived intensity of astringency.

The oral cavity area is connected to the nasal cavity through the nasopharynx retronasally (Saunder and Silver 2016). This allows orally perceived volatile chemesthetic compounds to have access inside the nasal region. Hence, retronasal chemesthesis can also be perceived on the chemical structure of foods. This could impact the intensity of the overall chemesthetic sensation.

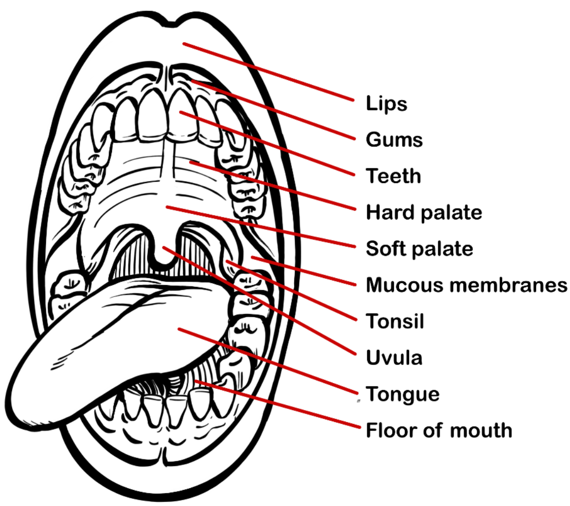


Figure 3. Anatomy of the oral region.

2.3.2. Food-related factors

Certain compounds that activate sensations such as taste, smell, or texture can show cross-modal interactions with chemesthesis. For example, fat and protein reductions in capsaicin oral pungency (Nolden et al. 2019; Gaiser and Hayes 2023; Gaiser and Hayes 2024). Similarly, fatty and creamy properties are suggested to reduce astringent properties due to the lubricating effect (De Wijk et al. 2003; Laaksonen 2011). This is why fatty and creamy foods may be used in masking unpleasant flavor properties. Increased sweetness elicited by sucrose can reduce the intensity of astringency (Lyman and Green 1990; Bajec and Pickering 2008; Laaksonen 2011; Törnwall 2013). Astringent components also activate bitterness, and a high intensity of bitterness may reduce the intensity of astringency (Bajec and Pickering 2008; Laaksonen 2011). Genetic variation in bitter taste receptor genes have been shown to interact with pungency, cooling, and astringency sensitivities indicating associations between chemesthesis and taste (**Appendix 1**). Interestingly, some taste compounds such as salts and acids can elicit oral chemesthesis (Stevens and Lawless 1986; Gilmore and Green 1993; Dessirier et al. 2001; Cayeux et al. 2023). To conclude, salts and acids creating oral irritation may also enhance chemesthesis such as cooling. In fact, coolants can enhance salty taste (Gray et al. 2008; Pringle 2016).

Since the oral cavity is connected to the nasal cavity, volatile irritants like allyl isothiocyanates found in radish, wasabi or mustard can activate nasal chemesthesis (Jordt et al. 2004; Staudinger 2019; Piochi et al. 2020). However, pungent capsaicin is a non-volatile compound and not likely to trigger orthonasal or ophthalmic (eye area) chemesthesis without physical contact. In comparison, volatile compound (Z)-propanethial S-oxide is a lachrymatory factor that causes eye irritation when released into the air during onion chopping (Silvaroli et al. 2017).

The temperature of foods containing chemesthetic ingredients may influence the chemesthetic perception. The pungent burning sensation of capsaicin can be enhanced by warmth and inhibited by the coldness of foods (Green, 1986). Additionally, capsaicin can intensify the sensation of warmth and reduce the intensity of coldness perceived in the oral cavity. In contrast, *l*-menthol solutions below the oral temperature have been rated as cooler than water of the same temperature (Green, 1985). Moreover, *l*-menthol can modulate the oral sensations of warmth and cold by enhancing coldness and attenuating the sensations of warmth. Interestingly, the astringency sensation may be perceived more intensively at body temperature rather than room temperature due to the protein-binding process (Peleg et al. 1998; Laaksonen 2011).

2.3.3. Age

Increasing chronological age can reduce chemosensory acuity, explaining why the low-level chemesthetic irritation in orange juice samples is preferred by older participants (*N*=57) (Forde and Delahunty 2004). However, not all senses decrease in acuity to the same extent, and there is complexity with increasing age. Another study showed that increasing age is not associated with the burning intensity of capsaicin nor the liking or yearly intake of hot chili peppers (Spinelli et al. 2018). Although the age of participants is often informed in chemesthesis-related research, few studies directly report associations between age and chemesthetic sensitivity.

2.3.4. Gender

The impact of personality traits (e.g., food neophobia, sensitivity to disgust, sensitivity to reward, sensitivity to punishment, sensitivity to reward, alexithymia, and private body consciousness) on the pungency of capsaicin has shown a complex set of differences between men and women in a large-scale study (Spinelli et al. 2018). Women rated the burning intensity of capsaicin-induced tomato juice lower than men (Nolden et al. 2019). Self-reported spice level has been associated with capsaicin perception, and men have shown higher scores compared to women (Nolden and Hayes 2017). Some studies that include the intensity measurements of capsaicin, primarily focus on reporting the consumption or liking of spicy foods rather than investigating direct gender differences in capsaicin sensitivity (Byrnes and Hayes 2015; Lyu et al. 2021; Lyu et al. 2023).

2.3.5. Health-related factors

Awareness of the important functional properties of chemical senses rose during the COVID-19 pandemic. The loss and impairment of chemical senses including smell (anosmia: loss of smell), taste (ageusia: loss of taste), and chemesthesis (neuropathy: disorders of peripheral nerve cells and fibers) caused concern among people and increased research interest of the mechanisms behind it (Parma et al. 2020; Algahtani et al. 2022; Weir et al. 2023; Hammi and Yeung 2024). Research has shown that COVID-19 infection causes the acute loss of oral chemesthesis from a jellybean (cinnamon burning) sample (Weir et al. 2023). The negative impacts of viruses and other pathogens on the sensory functions should be identified in research, and whether the effects are temporary or more permanent.

Chronic and high-risk-level alcohol consumption may lead to neuropathy, where nerve damage occurs (Sadowski and Houck 2024). This leads to deleterious effects on the central and peripheral nervous systems due to the direct toxic effects of alcohol. Thus, this can create tolerance towards the burning sensation of ethanol and cause severe painful health problems. The amount of ethanol that can cause peripheral neuropathy is still unknown (Chopra and Tiwari 2012), and there is no specific test to diagnose for this condition (Sadowski and Houck 2024).

Certain oral-area illnesses may increase the sensitivity of mucous membranes that may cause an unpleasant experience. A pungent capsaicin rinse treatment is used as a treatment for burning mouth syndrome due to its desensitizing impact (Di Stasio 2016). However, capsaicin first increases the burning sensation at the beginning of the treatment, which causes an unpleasant challenge for patients. However, head and neck cancer patients showed a lower somatosensory response to chemesthesis than control group without cancer, which is associated with their reduced salivary functions (Riantiningtyas et al. 2023). This may impact the eating experiences of patients with reduced salivary functions, which could lead to poor nutrition.

High capsaicin intake may have modest effects in reducing body mass index (BMI) for overweight or obese individuals (Zhang et al., 2023b). Capsaicin is said to reduce hunger through hormones and by increasing lipolysis in white adipose tissue and energy expenditure through brown adipose (Elmas and Gezer 2022). Despite this, some studies have shown that BMI is not associated with the frequent use of chilies (Lyu et al. 2021; Lyu et al. 2023).

Frequent smoking has been inked with lower taste sensitivity (Chéruel et al. 2017). A similar impact with nicotine is expected in chemesthetic sensitivity. However, cooling compound *l*-menthol can cross-desensitize nicotine-evoked oral chemesthesis by reducing harshness, which may account for its popularity as a flavor additive to tobacco products (Carstens and Carstens 2022).

2.3.6. Personality traits

Personality traits may influence the acceptability and consumption of chemesthetic foods (Prescott and Stevenson 1995; Byrnes and Hayes 2013; Byrnes and Hayes 2015; Spinelli et al. 2018). Personality differences or cognitive functions may account for the willingness to explore novel food sensations (Dalton and Byrnes 2016). A study has shown that certain personality traits such as sensation seeking and sensitivity to reward are differentially associated with the liking and intake of spicy foods in men and women (Byrnes and Hayes 2015). Similarly, another study discovered that differences between men and women in personality seemed to influence the intake of spicy foods (Spinelli et al. 2018).

Associations between the pungency perception and different personality traits including sensitivity to reward, sensitivity to punishment, sensitivity to disgust, private body consciousness, alexithymia (emotional blindness), and food neophobia (the fear or avoidance of novel foods) have been studied previously (Byrnes and Hayes 2013; Byrnes and Hayes 2015; Spinelli et al. 2018). Earlier research has shown that sensitivity to capsaicin is not associated with any personality measures (Byrnes and Hayes 2013). Personality traits such as neophobia and disgust sensitivity are related with pungency perception (Spinelli et al. 2018). That research has suggested that sensation seeking and sensitivity to reward would moderate the relationship between perceived burn intensity and the liking of spicy foods.

Different personality traits are linked to the experience of chemesthetic foods. In addition, genetics are seen as a baseline to the influence and experience of chemesthetic sensitivity and the liking of spicy foods (Prescott and Stevenson 1995; Törnwall 2013; Dalton and Byrnes 2016). The effects of social influence on chemesthetic food consumption can be impacted by the surrounding culture (Prescott and Stevenson 1995). For example, eating chili peppers has been linked with many "benignly masochistic" and thrill-seeking activities (Byrnes and Hayes 2013). To conclude, personality traits are complex, and more research is needed to understand associations between personality traits and chemesthesis.

2.4. Safety challenges of chemesthetic compounds

Certain challenges concerning the usage of chemesthetic ingredients in foods exist. Although chemesthetic compounds can have a positive impact on health (Mattes and Ludy 2016), some compounds can activate pain perception and have a negative impact (Dalton and Byrnes 2016; Hayes 2016; Ilie et al. 2019). As an example, ethanol can trigger migraines and headaches by stimulating TRP channels (Viana 2011; Benemei et al. 2014). In addition, ethanol is a toxic compound classified as a carcinogen (e.g., Rumgay et al., 2021).

The desire for strong chemesthetic sensations can be dangerous. European Union Law related to Food Safety (EC) no 178/2002 forbids unsafe products. The European Food Safety Authority (EFSA) has no regulation concerning the maximum concentration of capsaicin in food products (Finnish Food Authority 2024b). However, due to a lethal capsaicin poisoning case in USA that was caused by foods containing more than 11.8 mg per serving, some of the European National Food Authorities (e.g., Denmark and Finland) have given general warnings and even recommended banning those products from markets (Finnish Food Authority 2024b; Leblanc et al. 2024; Baggesen 2024). These safety aspects need more investigation and testing.

3. AIMS OF THE STUDY

The main aim for this research was to investigate individual differences in chemesthetic perception and its role in food-related behavior among adults as a part of the FoodTaste Finland Research Program: *Human taste sensitivity and multisensory perception of food*. In this research, intensity and recognition ratings were studied using clustering and score modeling following similar methods as in earlier taste sensitivity research (Puputti et al. 2018; Puputti et al. 2019a; Puputti et al. 2019b). Then, connections between chemesthesis and taste sensitivities were investigated. Explanatory demographic and health-related factors were investigated. Additionally, food-related behavior was studied focusing on the consumption and recalled pleasantness of F&B-items typical for the Nordic food culture. An unpublished dietary habits data set was also studied.

This dissertation aimed to study (the publication number in parenthesis):

A) Individuality of chemesthetic sensitivity and connections to taste sensitivity
Hypothesis 1. Individual differences exist (I)
Hypothesis 2. Chemesthetic sensitivity is associated with taste sensitivity (I)

B) Factors explaining individuality of chemesthetic perception
Hypothesis 3. Age and gender are explanatory factors (II)
Hypothesis 4. BMI and smoking status are explanatory factors (II)

C) Connections between chemesthetic sensitivity and food-related behavior
Hypothesis 5. Consumption and recalled pleasantness are linked to sensitivity (III)
Hypothesis 6. Dietary habits are linked to sensitivity (unpublished data)

4. MATERIAL AND METHODS

The research explores a chemesthesis sensory study data set and food-related behavior data set. The sensory study was conducted in the sensory laboratory (ISO-8589) at the Nutrition and Food Research Center at the University of Turku, Faculty of Medicine (Turku, Finland) before the COVID-19 pandemic. In addition, this doctoral research utilizes previous findings of taste sensitivity research that were obtained from the same study participants (Puputti et al. 2018; Puputti et al. 2019a; Puputti et al. 2019b; Puputti 2020).

4.1. Participants

The dataset for the chemesthesis research was collected from 205 volunteer participants. All the written and spoken communication was in Finnish. Participants were recruited using e.g., advertisements, websites, and public events. The exclusion criteria were pregnancy or lactating state, and all participants gave consent and were informed about health-related details including allergens of the samples. Participants were untrained, but they were first introduced to chemesthesis and samples briefly with verbal and written instructions. Before the actual evaluation of the chemesthetic samples, they tasted the second strongest concentration of each quality to familiarize themselves with the chemesthesis and to remove the element of surprise. The background information of the study participants presented in **Table 2** is based on several research publications (Puputti et al. 2018; Puputti et al. 2019a; Puputti et al. 2019b; Roukka et al. 2021; Roukka et al. 2023).

Table 2. Characteristics of study participants (table reprinted and edited with permission of the copyright owner).

Variable		*N*	%	Data missing (*N*)
Age	41.7 ± 15.2	205	100	0
	19–34	88	43	
	35–49	59	29	
	50–79	58	28	
Gender		205		0
	Women	164	80	
	Men	41	20	
BMI	25.6 ± 5.6	198	97	7
Lean individuals	<25.0	111	56	
Overweight individuals	25.0–29.9	51	26	
Obese individuals	>30.0	36	18	
Smoking		198		7
	Currently/Former	51	26	
	Nonsmoker	147	74	
Pungency sensitivity elicited by capsaicin		199		6
Hyposensitive	CSG1	56	28	
Semi-sensitive	CSG2	59	30	
Hypersensitive	CSG3	84	42	
Cooling sensitivity elicited by *l*-menthol		198		7
Hyposensitive	MSG1	81	41	
Semi-sensitive	MSG2	96	48	
Hypersensitive	MSG3	21	11	
Astringency sensitivity elicited by aluminum ammonium sulfate		197		8
Hyposensitive	ASG1	91	46	
Semi-sensitive	ASG2	62	32	
Hypersensitive	ASG3	44	22	
Combined oral chemesthetic sensitivity		196		9
Hyposensitive	COCSG1	59	30	
Semi-sensitive	COCSG2	105	54	
Hypersensitive	COCSG3	32	16	

4.2. Chemesthetic samples

The evaluated sample series included prototypic compounds for pungency, cooling, and astringency at different concentrations from the lowest (A) to the highest (E) (**Table 3**). All samples and concentration levels were pre-tested before the data collection. Concentrations were determined experimentally by using quarter logarithmic dilution series. The samples were used to measure intensity and chemesthetic quality recognition.

Samples were diluted with active carbon filtered water and stored in glass bottles in the refrigerator following good laboratory practice. Capsaicin and *l*-menthol samples were first diluted into a glyceryl tri-acetate solution; after that, created stock solutions were diluted with active carbo-filtered water. All the solutions were prepared less than four days before the evaluation sessions and samples were served at room temperature. The sample series included one water sample representing the neutral "zero" stimuli, which was excluded from the analyses.

Table 3. Chemesthetic sample series (table reprinted and edited with permission of the copyright owner).

Chemesthetic quality	Prototypic compound	A	B	C	D	E
Pungency	[a] Capsaicin (CAS: 404-86-4)	0.049 µM	0.088 µM	0.154 µM	0.275 µM	0.491 µM
Cooling	[b] *l*-Menthol (CAS: 2216-51-5)	0.013 mM	0.023 mM	0.040 mM	0.072 mM	0.128 mM
Astringency	[c] Aluminum ammonium sulfate (CAS: 7784-26-1)	0.22 mM	0.39 mM	0.70 mM	1.24 mM	2.21 mM

Note:

[a] Fluka Sigma-Aldrich (St. Lous, Missouri, USA), $C_{18}H_{27}NO_3$, >98.5%

[b] Symrise (Holzminden, Germany), $C_{10}H_{20}O$, >99.7%

[c] Produced by Sigma-Aldrich (St. Louis, Missouri, USA), $AlNH_4(SO_4)^2 \cdot 12H_2O$, >99.0%

Dilutions: A–E

4.3. Sensory evaluation procedure

The sensory evaluation procedure started with the participants neutralizing their mouth with water and unsalted crackers (as well as between the samples). Then, they were guided to pour the entire sample (5 mL each) into their mouth, swish it around for five seconds and then spit it out. After that, they were guided to wait for a moment due to the possible delay of the stimuli. Then, participants were asked to select the recognized stimuli from given options (astringency, pungency, cooling, metallic, or water) and rate the overall intensity of the sample on a line-scale (0–10). The scale was anchored both verbally and numerically from 0 to 10 (0="no sensation", 2="very mild", 4="quite mild", 6="quite strong", 8="very strong", and 10="extremely strong").

4.4. Questionnaires for background factors and food-related behavior

Background information (gender, age, education, smoking habits, and weight and height for BMI) and food-related behavior data were collected using the Webropol online questionnaire (Webropol Inc., Helsinki, Finland). Food-related behavior questions focused on the consumption and recalled pleasantness of F&B-items typical for Nordic food culture. In addition, eating behavior questions were included. Participants were instructed to rate only familiar F&B-items.

A use-frequency questionnaire with a 6-point category scale (1="never or very seldom", 2="a few times per year", 3="once or twice per month", 4="once per week", 5="a few times per week", and 6="daily") was used to measure the consumption of F&B-items. Additionally, a 7-point category scale (1="I do not drink at all", 2="0–1", 3="2–3", 4="4–6", 5="7–9", 6="10–13", and 7="14 or more" doses per week: DPW) was used to measure the consumption of mild (<8%), medium (8–21%), and strong (>21%) alcoholic beverages.

A 9-point hedonic scale (1="dislike extremely", 2="dislike very much", 3="dislike moderately", 4="dislike slightly", 5="neither like nor dislike", 6="like slightly", 7="like moderately", 8="like very much", and 9="like extremely") was used to measure the recalled pleasantness of F&B-items. The option "I cannot say" was also available.

Eating behavior was studied with 15 questions related to dietary habits and measured with a 6-point categorical scale (1="I do not consume or cook", 2="never or very seldom", 3="rarely", 4="occasionally", 5="often", and 6="always").

4.5. Data processing methods

Data was collected using Compusense Plus 5.6 software (Compusense Inc., Guelph, ON, Canada). Statistical analysis for this part of the research was performed with IBM SPSS Statistic 28.0 (IBM Corporation, Armonk, NY, USA). Unscrambler X 10.5.1 (CAMO Software, Oslo, Norway) was used for PLS regression modeling. The following information is about the data processing methods used in this dissertation.

4.5.1. Article I

Intensity results of each prototypic chemesthetic sample series were first explored with hierarchical clustering. An agglomerative hierarchical clustering was performed with the squared Euclidean distances using Ward's method to study chemesthetic intensity. Then, a three-cluster model was chosen to achieve sufficient cluster size, and it was applied to study three qualities: pungency, astringency, and cooling. By comparing the average intensity of each formed cluster, three sensitivity groups were identified. The differences between sensitivity groups (hyposensitive, semi-sensitive, and hypersensitive) were examined by multivariate analysis of variance (MANOVA) with *post-hoc* tests (Tukey's HSD).

A novel oral chemesthetic sensitivity score was created following similar methodology as a previously studied taste sensitivity score model (Puputti et al. 2018). The oral chemesthetic sensitivity score model was built based on the average from pungency (capsaicin), cooling (*l*-menthol), and astringency (aluminum ammonium sulfate) sensitivity groups. Based on generated scores, seven sensitivity groups were created (1.00, 1.33, 1.67, 2.00, 2.33, 2.67, and 3.00). Then, these sensitivity groups were classified into hyposensitive (1.00 and 1.33), semi-sensitive (1.68, 2.00, and 2.33), and hypersensitive (2.67 and 3.00).

Correlation tests were performed to study associations between sensitivity groups and scores. These included results from chemesthetic qualities (pungency, coolness, astringency, and combined) and taste modalities (bitter, salty, sour, sweet, umami, and overall taste sensitivity score).

Multinomial logistic regression (MNLR) models were performed to study interactions among sensitivity groups. The first models included only chemesthetic qualities, and other models explained interactions between chemesthesis and taste cluster data. In both phases, we used forward and backward stepwise selection techniques. The largest clusters from each modality were chosen as a reference category in every case and the criterion significance was $p<0.05$. If the odds ratio (OR) was less than 1.00, then the explaining factor was 1/OR times more likely to belong to the reference group instead of the dependent group.

4.5.2. Article II

Oral chemesthetic quality recognition was studied from the prototypic sample series (capsaicin for pungency, *l*-menthol for cooling, and aluminum ammonium sulfate for astringency). From the correct prototypic recognition results, the novel chemesthesis recognition score was modeled. Based on the generated scores, individuals were classified into oral chemesthetic recognition groups "better recognizers" (4.00–5.00), "poorer recognizers" (0–2.00), and "average recognizers" (2.33–3.67). Differences between chemesthetic sensitivity, recognition, and background variables were studied using chi-squared test, and Kruskal–Wallis and Mann–Whitney *U* tests, and associations with Spearman's rank correlation test.

Factors explaining sensitivity to prototypic chemesthetic compounds were studied using MNLR modeling. Potential predictors were gender, age, BMI, smoking status, and quality-recognition. Gender and smoking status were entered as dichotomous variables and age, BMI, and quality recognition as continuous variables. The largest and second largest groups in prototypic chemesthetic compound–based sensitivity were selected as the reference group for the model.

4.5.3. Manuscript III

Spearman's rank correlation test was used to investigate associations between chemesthetic sensitivity and both consumption and recalled pleasantness ratings of F&B-items. Then, to reveal the most significant connections and to lower the Type I risk, MANOVA and non-parametric tests (Kruskal–Wallis and Mann–Whitney *U* tests) with adapted *post-hoc* tests were used to investigate the differences between chemesthetic sensitivity groups.

Multi-hierarchical linear regression was used to investigate associations with F&B-components defined by Puputti et al. (2019b). PLS regression modeling was used for F&B categories illustrating interactions between use-frequency ratings and recalled pleasantness within chemesthetic sensitivity groups.

4.5.4. Dietary habits

Spearman's rank correlation test was used to study associations between chemesthetic sensitivity groups and dietary habits. One-way ANOVA and non-parametric tests (Kruskal–Wallis and Mann–Whitney *U*) with adapted *post-hoc* tests were used to investigate the impact of chemesthetic sensitivity on the dietary habits that showed correlation.

4.6. Ethical aspects

The sensory study was reviewed by the Institutional Review Board of the Southwest Finland Hospital District's Ethics Committee (145/1801/2014) and followed the European Union's General Data Protection Regulation (GDPR) guidelines. The sensory facilities followed the general guidance for the design of test room standards (ISO 8589). Volunteer participants signed the informed consent form that explained the general structure and necessary details about the research. Some chemesthetic compounds can stimulate pain, which can be perceived as unpleasant. The participants were able to drop out whenever they wanted. After the evaluation the participants were thanked and rewarded with a small food gift as a compensation for their participation.

5. RESULTS

This section focuses on addressing the results of this study.

5.1. Individuality of chemesthetic sensitivity and connections to taste sensitivity (I)

Chemesthetic sensitivity data was investigated using a hierarchical clustering method to reveal quality-specific differences. Quality-specific sensitivity groups were identified (cluster 1=”hyposensitive”, cluster 2=”semi-sensitive”, and cluster 3=”hypersensitive”) (**Figure 4–6**). In addition, a combined oral chemesthetic sensitivity score and groups were modeled. A relationship between chemesthetic sensitivity and taste sensitivity was discovered.

5.1.1. Quality-specific chemesthetic sensitivity groups

Pungency (capsaicin) sensitivity (**Figure 4)** showed that cluster 3 differed from clusters 1 and 2 for each concentration (**Table 3**), but cluster 2 did not differ from cluster 1 at concentrations A (0.049 µM), B (0.088 µM), and C (0.154 µM). Thus, the higher capsaicin concentrations D (0.275 µM) and E (0.491 µM) revealed the sensitivity groups more clearly than the lower concentrations A, B, and C.

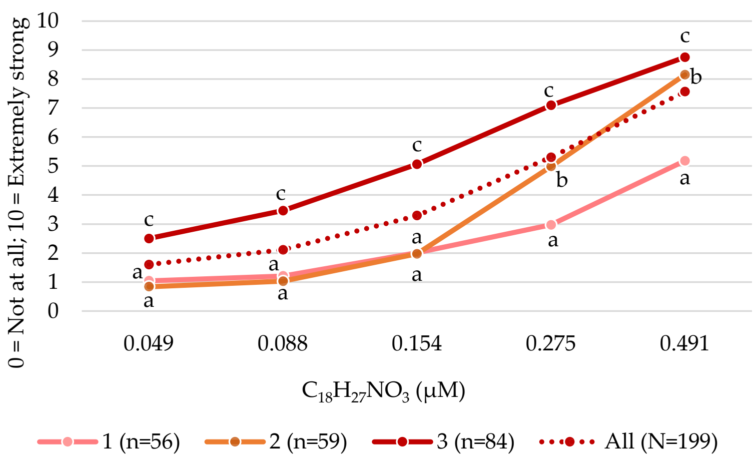


Figure 4. Pungency (capsaicin) sensitivity clusters (1=”hyposensitive”, 2=”semi-sensitive”, and 3=”hypersensitive”) and intensity results. Participants evaluated samples and rated intensity on a line scale from 0 (Not at all) to 10 (Extremely strong). Multivariate analysis of variance with applied Tukey’s HSD *post-hoc* test (a, b, and c) revealed different and similar intensity ratings among clusters at each concentration level.

Cooling (*l*-menthol) sensitivity (**Figure 5**) showed that intensity ratings of each cluster differed in every concentration (**Table 3**): A (0.013mM), B (0.023mM), C (0.040mM), D (0.072mM), and E (0.128mM). However, the number of participants in the hypersensitive group (cluster 3: 11%) was relatively small compared to other groups.

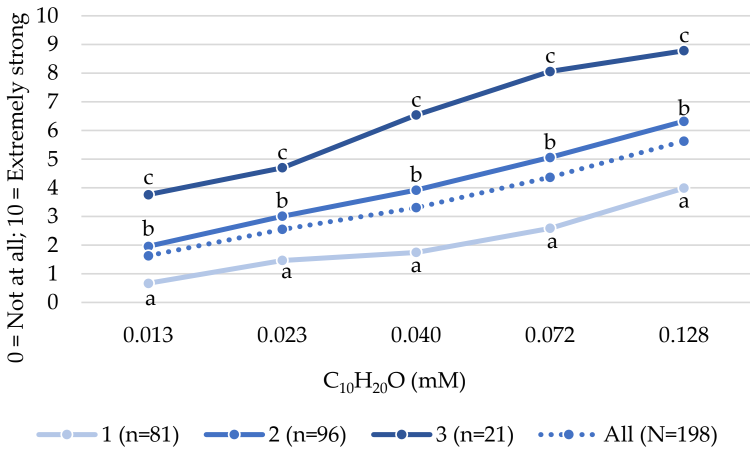


Figure 5. Cooling (*l*-menthol) sensitivity clusters (1="hyposensitive", 2="semi-sensitive", and 3="hypersensitive") and intensity results. Participants evaluated samples and rated intensity on a line scale from 0 (Not at all) to 10 (Extremely strong). Multivariate analysis of variance with applied Tukey's HSD *post-hoc* test (a, b, and c) revealed different and similar intensity ratings among clusters at each concentration level.

Astringency (aluminum ammonium sulfate) sensitivity (**Figure 6**) was the most challenging to model. Intensity results showed that cluster 2 differed from cluster 3 at all sample concentrations (**Table 3**). On the contrary, cluster 2 differed from cluster 1 at concentrations C (0.70mM), D(1.24mM), and E (2.21mM), but not at A (0.22mM) or B (0.39mM). Thus, identification of the semi-sensitive group was challenging for astringency sensitivity and needed a careful cluster comparison.

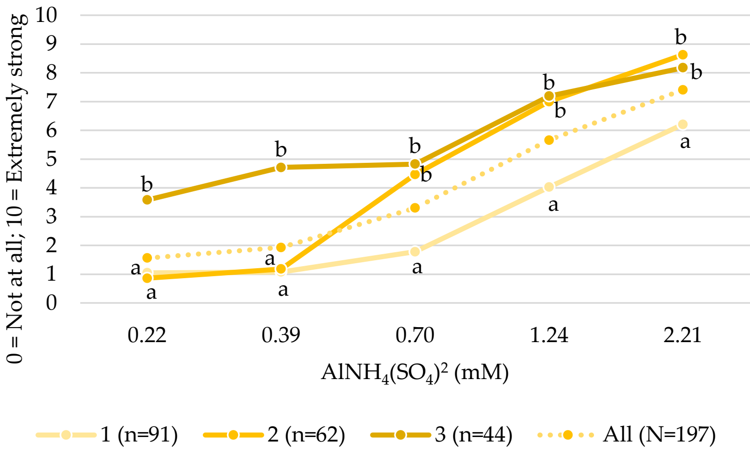


Figure 6. Astringency (aluminum ammonium sulfate) sensitivity clusters (1="hyposensitive", 2="semi-sensitive", and 3="hypersensitive") and intensity results. Participants evaluated samples and rated intensity on a line scale from 0 (Not at all) to 10 (Extremely strong). Multivariate analysis of variance with applied Tukey's HSD *post-hoc* test (a and b) revealed different and similar intensity ratings among clusters at each concentration level.

5.1.2. Combined oral chemesthetic sensitivity

To generalize oral chemesthesis, a score model for combined oral chemesthetic sensitivity was created based on the average intensity ratings in each quality-specific sensitivity group (pungency, cooling, and astringency). After this, combined oral chemesthetic sensitivity groups were defined by dividing the possible maximum score by three and exploring the ranges. The score ranges were: hyposensitive=1.00–1.33, semi-sensitive=1.67–2.33, and hypersensitive=2.67–3.00 (**Figure 7**). This novel sensitivity score and group modeling revealed that 16% (*N*=196) are more sensitive in all chemesthetic dimensions among participants. Furthermore, 30% were less sensitive and the majority of the participants (54%) were classified into the semi-sensitive group.

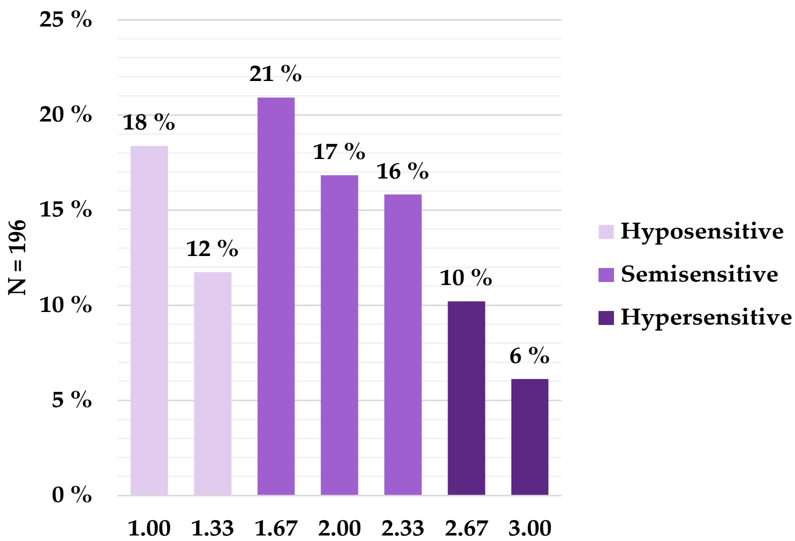


Figure 7. Participants were divided into different sensitivity groups (hyposensitive *n*=59, semi-sensitive *n*=105, and hypersensitive *n*=32), based on their oral chemesthetic sensitivity score (CSS) value presented on the X-axis. The number of participants in each group is shown on the Y-axis (figure reprinted and edited with permission of the copyright owner).

5.1.3. Associations between chemesthesis and taste

Chemesthetic sensitivity and taste sensitivity generally had positive correlations. The taste sensitivity score and combined oral chemesthetic sensitivity score showed a meaningful level of association (r=0.56**). This positive association suggests that higher chemesthetic sensitivity can indicate higher sensitivity to taste and vice versa.

Chemesthesis and taste had connections between each of the chemesthesis and taste dimensions that were observed with the MNLR models presented. Pungency was explained by sour, sweet, and bitterness, and cooling by sour, sweet, and bitter. Astringency sensitivity was explained by all taste modalities. In contrast, sour taste was explained by astringency and cooling; sweet taste by pungency, cooling, and astringency; salty taste by astringency and pungency; and bitterness by pungency and cooling.

5.2. Factors explaining individuality of chemesthetic perception (II)

The potential factors explaining individual differences among chemesthetic sensitivity groups were investigated by focusing on prototypic compounds. In addition to sensitivity, recognition data was also explored and modeled to understand how participants identified the prototypic samples.

5.2.1. Recognition of chemesthesis

In general, the recognition results (**Figure 8**) showed that prototypical chemesthetic sensation became clearer as concentrations increased. Capsaicin samples were identified as pungency (**Figure 8a**), *l*-menthol samples as cooling (**Figure 8b**), and aluminum ammonium sulfate samples as astringency (**Figure 8c**) by the highest number of participants at each concentration level. However, results showed that there were some participants that identified and selected different sensations than the prototypical one, especially at lower concentrations. These prototypical compound-based recognition results were then generated as combined oral chemesthetic recognition score that enabled classifying into better, average, and poorer recognizers (**Figure 9).** Based on this generalized combined oral recognition score model, most participants were classified as average recognizers (66%). Better recognizers (26%) were the second largest group, and only a few participants belonged to the poorer recognizers group (8%).

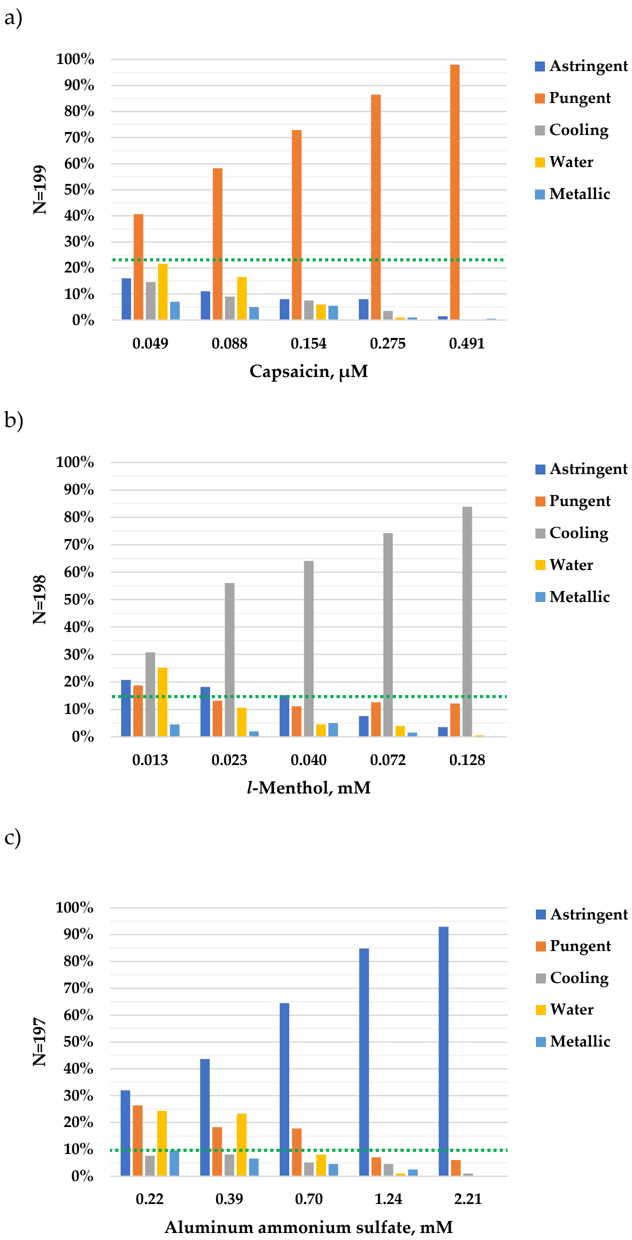


Figure 8. Oral chemesthetic quality recognition results for (a) capsaicin, (b) *l*-menthol, and (c) aluminum ammonium sulfate solutions. The participants could choose only one quality per sample (astringency, pungency, cooling, metallic, or water). The green dotted line indicates the level of participants who selected (a) only pungency from capsaicin samples (23%), (b) only cooling from *l*-menthol samples (15%), and (c) only astringency from aluminum ammonium sulfate samples (10%) (figure reprinted and edited with permission of the copyright owner).

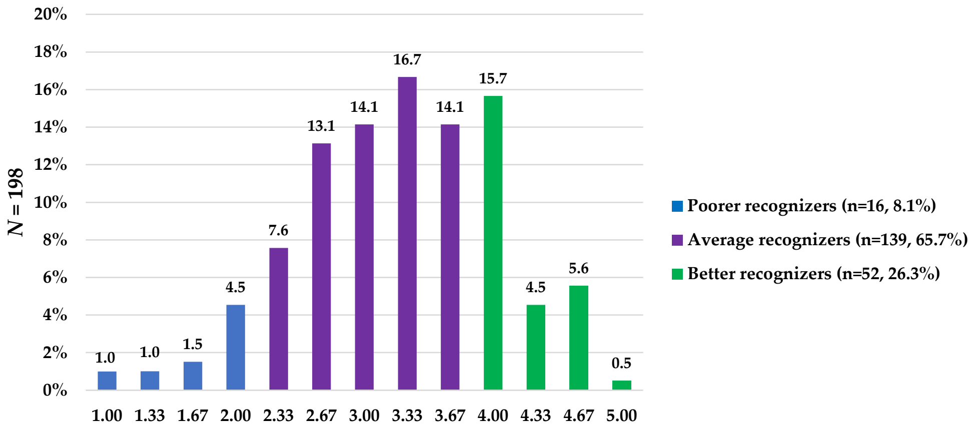


Figure 9. The distribution of combined oral chemesthetic recognition score (0-5.00) created from pungency, cooling, and astringency recognition results (*N*=198). Getting 0 for this score is theoretically possible, however, none of the participants got 0 correct (figure reprinted and edited with permission of the copyright owner).

5.2.2. Predictors for sensitivity

MNLR results revealed associations between selected background factors: gender, age, BMI, smoking status, and recognition score. Results showed that pungency (capsaicin) sensitivity was explained by gender, age, and recognition score. Women were more sensitive to pungency than men. Increasing age indicated lower sensitivity and increasing recognition score indicated higher sensitivity. In addition, cooling (*l*-menthol) and astringency (aluminum ammonium sulfate) sensitivity were explained by age and recognition scores. In both cases, increasing age and recognition scores predicted higher sensitivity. BMI and smoking status did not explain chemesthetic sensitivity.

5.3. Connections between chemesthetic sensitivity and food-related behavior (III)

The food-related behavior data was investigated in this part of the research together with chemesthetic sensitivity data (I). The focus was on the consumption and recalled pleasantness of F&B-items (*N*=64) that are typical in Nordic food culture.

5.3.1. Sensitivity connections to consumption and recalled pleasantness

Different chemesthetic sensitivity dimensions, including pungency, cooling, astringency, and combined, had connections between consumption and recalled pleasantness of specific F&B-items. These included foods that can have chemesthetic properties such as *blue cheese*, *Brussel's sprouts*, *chili*, *chili sauce*, *radish*, *salmiak*, *soy sauce*, *strong alcohol*, *medium alcohol*, and *vegetable purée soup*. Women, in particular, showed connections between cooling sensitivity and consumption of *chili* and *soy sauce.* Additionally, preliminary research for men showed connections between *blue cheese, celery, sea buckthorn, candy, ketchup, potato chips, milk chocolate, red wine, white wine, strong alcohol, medium alcohol, soft drinks,* and *sweet pastry.* Generally, less sensitive individuals seemed to have higher consumption and recalled pleasantness ratings for F&B with chemesthetic properties than those who were more sensitive. Preliminary results indicated that men may have connections between chemesthetic sensitivity and both consumption and recalled pleasantness of certain fatty-salty-sweet foods and alcoholic beverages.

5.3.2. Multidimensional interactions

Among all participants, PLS regression models for F&B categories revealed multidimensional interactions between consumption and recalled pleasantness within chemesthetic sensitivity groups. These models showed stronger connections between sensitivity and consumption and recalled pleasantness in F&B-items that belonged to the categories of "vegetables, vegetable dishes, and pungent sauces" and "alcoholic and non-alcoholic beverages". In addition, multivariate hierarchical regression results were structured using F&B categories by Puputti et al. (2019b). The results revealed that cooling sensitivity was the only chemesthetic dimension predicting consumption and recalled pleasantness of salty and savory foods, and the consumption of fatty foods.

5.4. Chemesthetic sensitivity and dietary habits

Eating behavior was studied from the unpublished dietary habits dataset that included variables listed in **Table 4**. The main results are introduced and concluded here.

Table 4. List of dietary habits variables and definition for statistical testing procedure among all participants. Levene's Test of Equality of Error Variances defines whether the variables are processed with parametric tests (ns, $p \geq 0.05$) or non-parametric tests (sig, $p < 0.05$).

Dietary habits	Total *N*=194	Pungency		Cooling		Astringency		Combined	
$N_{(variable)}$=18	mean ± std.dev.	ns	sig	ns	sig	ns	sig	ns	sig
Add milk to coffee	3.94 ± 2.08	x		x		x		x	
Add cream to coffee	2.39 ± 1.02	x		x		x		x	
Add sugar to coffee	2.21 ± 1.11	x		x		x		x	
Add sweetener to coffee	1.99 ± 0.80	x		x		x		x	
Add sugar or honey to tea	3.60 ± 1.49	x			x	x		x	
Add sweetener to tea	2.17 ± 0.71	x		x		x		x	
Add milk to tea	2.84 ± 1.35		x		x	x			x
Add salt to vegetable boiling cooking water	4.05 ± 1.42	x		x		x		x	
Add salt to food	3.34 ± 1.04	x		x		x		x	
Add aromatic salt to food	2.47 ± 0.77	x		x		x		x	
Add ketchup to food	3.27 ± 0.83		x	x		x			x
Add soy sauce to food	2.93 ± 0.84	x		x		x		x	
Use cream in cooking	4.20 ± 0.73	x		x		x		x	
Use cheese in cooking	4.10 ± 0.70	x		x		x		x	
Add sugar to berries	3.56 ± 1.11		x		x	x		x	
Eating vegetables	5.55 ± 0.77	x			x	x			x
Eating fruits	4.60 ± 1.15		x	x		x		x	
Eating berries	3.66 ± 1.29	x		x		x		x	

5.4.1. Associations between sensitivity and habits

Chemesthetic sensitivity (pungency, cooling, astringency, and combined) had associations with dietary habits (**Table 5**)**.** Among men participants, a higher sensitivity to astringency increased the habit of adding sugar to coffee (ϱ^2 x 100=13%), adding ketchup to foods (18%), adding sugar or honey to berries (13%), and eating fruits (15%). A higher sensitivity to pungency increased the habit of adding milk to coffee (28%) and adding sugar or honey to tea (14%) among men. In addition, a higher sensitivity to cooling also increased to the habit of adding ketchup to foods (14%). Men with a higher combined oral chemesthetic sensitivity had a higher frequency of adding milk (14%) to coffee and adding ketchup to foods (14%). Results on all participants together and women participants separately showed only weak associations (less than 10%) between sensitivity and dietary habits.

Table 5. Spearman's correlation matrix between chemesthetic sensitivity and different dietary habits (1="I do not consume or cook"; 6="always") from all the participants together and between genders.

Dietary habits	**[A]Pungency sensitivity**			**[B]Cooling sensitivity**			**[C]Astringency sensitivity**			**[D]Combined sensitivity**		
	All	**W**	**M**	**All**	**W**	**M**	**All**	**W**	**M**	**All**	**W**	**M**
Add milk to coffee	**0.23****	0.15	**0.53****	-0.04	-0.08	0.16	-0.04	-0.09	0.14	0.07	0.02	**0.40***
Add milk to tea	-0.07	-0.14	0.18	**-0.16***	**-0.23****	0.10	-0.08	-0.13	0.11	**-0.18***	**-0.23****	0.10
Add sugar to coffee	0.01	-0.07	0.14	-0.08	-0.13	0.11	-0.10	**-0.22***	**0.36***	-0.05	-0.15	0.27
Add sugar or honey to tea	0.07	0.02	**0.37****	**-0.18***	**-0.23***	-0.21	-0.03	-0.05	0.05	-0.07	-0.10	-0.07
Add salt to vegetable boiling cooking water	-0.07	-0.08	-0.02	**-0.19****	**-0.24****	0.15	-0.10	-0.12	0.04	-0.12	-0.14	0.01
Add ketchup to foods	0.02	0.04	0.02	0.06	0.02	**0.36***	**0.17***	0.12	**0.42***	0.09	0.04	**0.37***
Add soy sauce to foods	-0.07	-0.05	-0.12	**-0.17***	**-0.19***	-0.06	0.01	0.01	0.17	-0.09	-0.12	0.07
Add sugar or honey to berries	0.06	0.04	0.15	-0.07	-0.14	0.25	0.02	-0.06	**0.36***	0.04	-0.02	0.27
Eating berries	0.10	0.12	-0.01	0.08	0.09	-0.04	0.09	**0.16***	-0.24	0.06	0.11	-0.15
Eating fruits	-0.13	**-0.24****	0.04	-0.02	-0.06	-0.02	-0.10	-0.06	**0.39***	**-0.16***	**-0.20***	-0.10

Significant correlation ratings (2-tailed) are **bolded: **** $p<0.01$, and * $p<0.05$

[A.]Pungency sensitivity elicited by capsaicin (N=199), [B]Cooling sensitivity elicited by *l*-menthol (N=198), [C]Astringency sensitivity elicited by aluminum ammonium sulfate (N=197), and [D]Combined oral chemesthetic sensitivity (N=196)

W(women, 80%) and M(men, 20%)

5.4.2. Impact of sensitivity on habits

- Pungency

In the case of pungent sensitivity groups, participants who were hyposensitive less frequently added milk to coffee than semi-sensitive or hypersensitive classified individuals ($F_{(2)}$=6.19, p<0.01, N=159 in **Figure 10**).

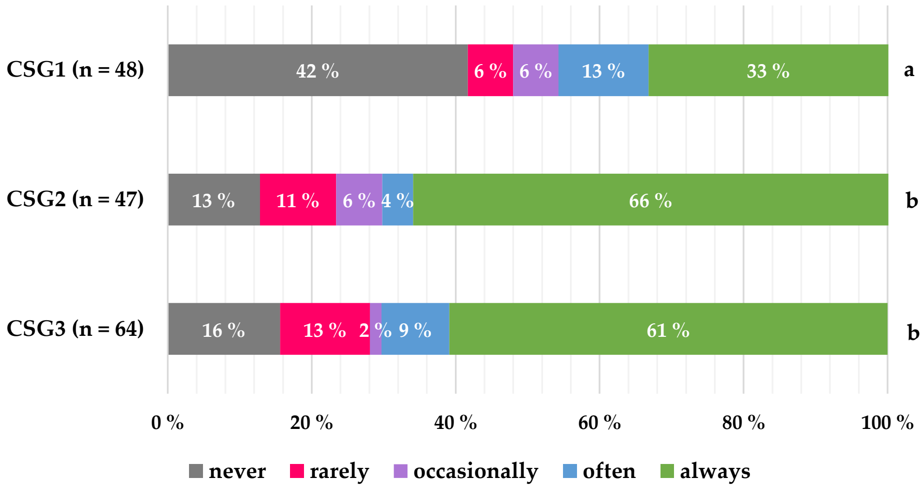


Figure 10. Results regarding adding milk to coffee (N=159), illustrating group differences between pungency (capsaicin) sensitivity groups: CSG1 (hyposensitive), CSG2 (semi-sensitive), and CSG3 (hypersensitive). Differences were studied using one-way ANOVA tests with Tukey's HSD *post-hoc* test (a and b).

Women participants showed differences between sensitivity groups in the habit of eating fruits ($H_{(2)}$=8.94, p<0.01, N=150). Hyposensitive women were eating fruits more frequently (4.10 ± 0.88) than the hypersensitive group (3.42 ± 1.14). Hyposensitive men were less frequently 1) adding milk to coffee: 1.67 ± 1.33 ($F_{(1)}$=6.48, p<0.05, N=30) and 2) adding sugar or honey to tea: 2.27 ± 1.34 ($F_{(1)}$= 5.05, p<0.05, N=36) compared to more sensitive (S+H) men: 1) 3.00 ± 1.58 and 2) 3.29 ± 1.34, respectively.

- Cooling

Cooling sensitivity groups showed differences between the following consumption behavior variables: add sugar or honey to tea ($H_{(2)}$=9.79, p<0.01, N=188, in **Figure 11**), add salt to boiling vegetable cooking water ($F_{(2)}$=3.74, p<0.05, N=193 in **Figure 12**), and add soy sauce to food while eating ($F_{(2)}$=4.26, p<0.05, N=192, in **Figure 13**). Participants classified as hypersensitive were less frequently adding sugar to tea than those who were hyposensitive and semi-sensitive. Participants that were hypersensitive to cooling were less frequently adding salt to vegetable boiling cooking water and adding soy sauce to foods while eating than hyposensitive individuals. Furthermore, hyposensitive participants were more frequently adding milk to tea than hypersensitive individuals ($H_{(2)}$=7.12, p<0.05, N=185, in **Figure 14**).

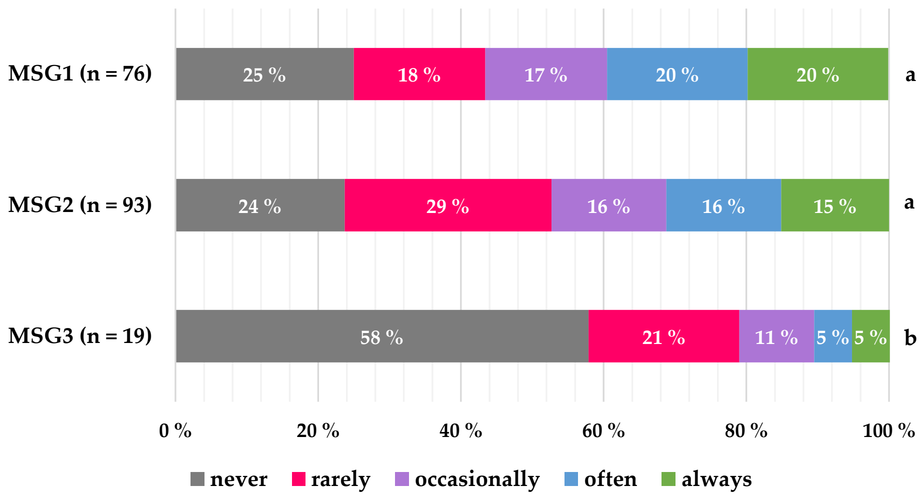


Figure 11. Results regarding adding sugar or honey to a tea (N=188), illustrating group differences between cooling (*l*-menthol) sensitivity groups: MSG1 (hyposensitive), MSG2 (semi-sensitive), and MSG3 (hypersensitive). Differences were studied using Kruskal–Wallis tests with pair-wise comparison (a and b).

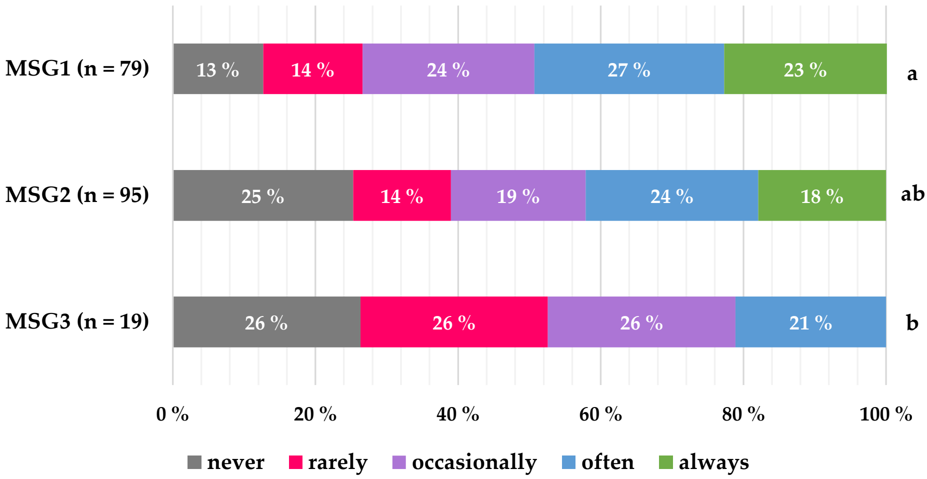


Figure 12. Results regarding adding salt to vegetable boiling cooking water (*N*=193), illustrating group differences between cooling (*l*-menthol) sensitivity groups: MSG1 (hyposensitive), MSG2 (semi-sensitive), and MSG3 (hypersensitive). Differences were studied using one-way ANOVA tests with Tukey's HSD *post-hoc* test (a,b, and ab).

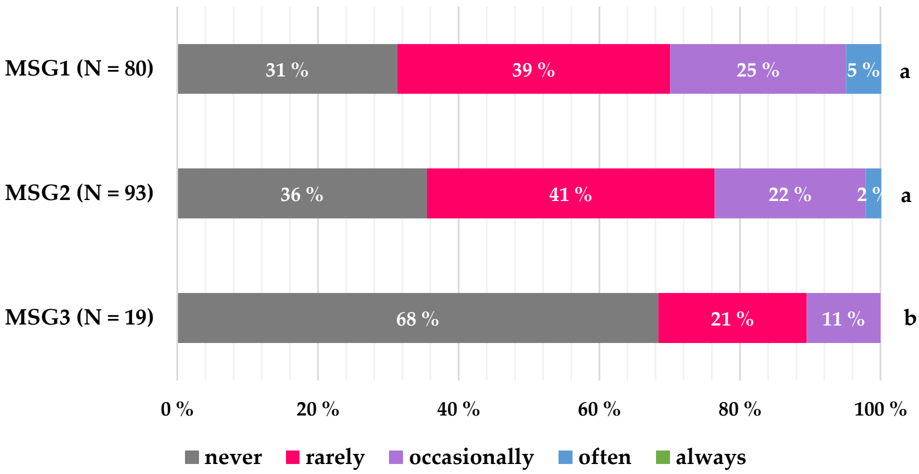


Figure 13. Results regarding adding soy sauce to food when eating it (*N*=192), illustrating group differences between cooling (*l*-menthol) sensitivity groups: MSG1 (hyposensitive), MSG2 (semi-sensitive), and MSG3 (hypersensitive). Differences were studied using one-way ANOVA tests with Tukey's HSD *post-hoc* test (a and b).

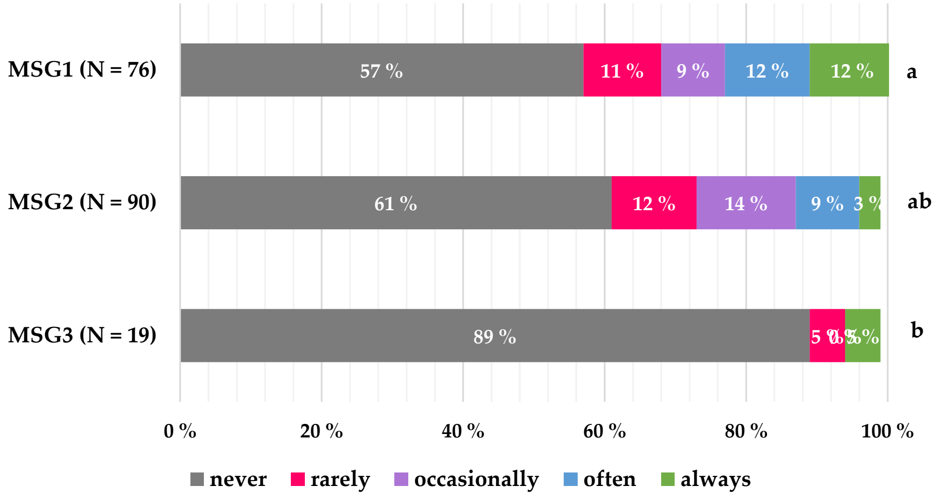


Figure 14. Results regarding adding milk to tea (*N*=185), illustrating group differences between cooling (*l*-menthol) sensitivity groups: MSG1 (hyposensitive), MSG2 (semi-sensitive), and MSG3 (hypersensitive). Differences were studied using Kruskal–Wallis tests with pair-wise comparison (a and b).

Women that were hyposensitive were more frequently 1) adding milk to tea: 2.31 ± 1.53 (H=8.90, p<0.05, N=147), 2) adding salt to boiling vegetable cooking water: 3.35 ± 1.25 ($F_{(2)}$=4.43, p<0.05, N=152), and 3) adding soy sauce to foods: 1.98 ± 0.83 ($F_{(2)}$=3.33, p<0.05, N=152) than hypersensitive women: 1) 1.28 ± 0.96, 2) 2.50 ± 1.10, and 3) 1.44 ± 0.71. Men that were hyposensitive were less frequently adding ketchup to foods: 2.00 ± 0.66 ($F_{(1)}$=4.57, p<0.05, N=37) than more sensitive (S+H) men: 2.53 ± 0.84, respectively.

- Astringency

Astringent sensitivity groups differed in the dietary habit of adding ketchup to foods ($F_{(2)}$=4.26, p<0.05, N=193, in **Figure 15**). Hyposensitive participants were less frequently adding ketchup to a meal than semi-sensitive individuals. Moreover, visual inspection showed that hyposensitive participants had the highest percentage of rarely and never user categories in comparison with semi-sensitive and hypersensitive individuals.

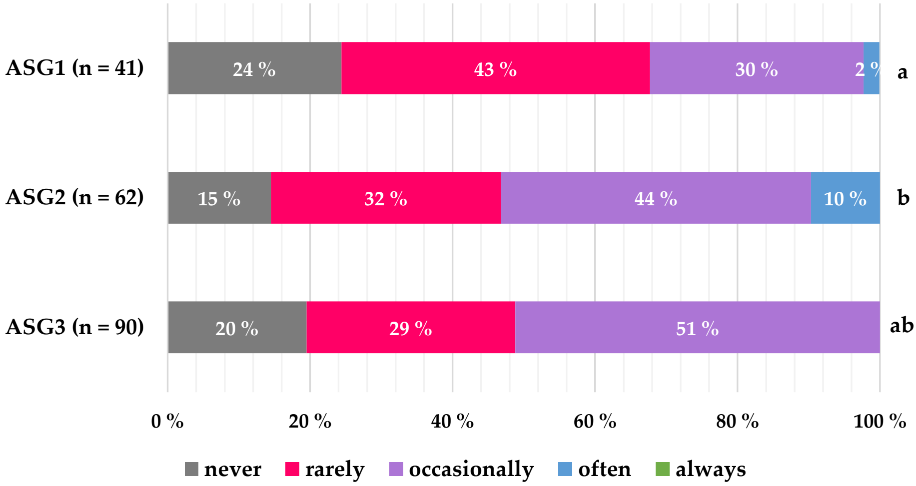


Figure 15. Results regarding adding ketchup to a food when eating it (N=193) illustrating group differences between astringency (aluminum ammonium sulfate) sensitivity groups: ASG1 (hyposensitive), ASG2 (semi-sensitive), and ASG3 (hypersensitive). Differences were studied using one-way ANOVA tests with Tukey's HSD *post-hoc* test (a,b, and ab).

Women showed differences between astringency sensitivity groups and habits of eating berries ($F_{(2)}$=3.37, p<0.05, N=153). Hypersensitive women had a more frequent habit of eating berries (mean ± std. dev.: 3.21 ± 1.27) than hyposensitive (2.57 ± 1.31) or semi-sensitive (2.56 ± 1.21) women. Hyposensitive men were less frequently 1) adding ketchup to foods: 2.00 ± 0.74 ($F_{(1)}$=7.51, p<0.01, N=37), 2) adding sugar or honey to berries: 2.30 ± 1.06 ($F_{(1)}$=5.02, p<0.05, N=37), and were more frequently 3) eating fruits: 3.57 ± 1.20 ($F_{(1)}$=5.62, p<0.05, N=37), compared to more sensitive (S+H group) men: 1) 2.67 ± 0.72, 2) 3.07 ± 0.96, and 3) 2.67 ± 1.05, respectively.

- Combined

Combined oral chemesthetic sensitivity groups differed in the dietary habit of adding milk to tea. Results revealed that those who were hyposensitive were more frequently adding milk to tea than hypersensitive individuals ($H_{(2)}$=7.00, p<0.05, N=183, in **Figure 16**). In addition, hyposensitive individuals were eating more fruits than hypersensitive individuals ($F_{(2)}$=3.12, p<0.05, N=188, in **Figure 17**).

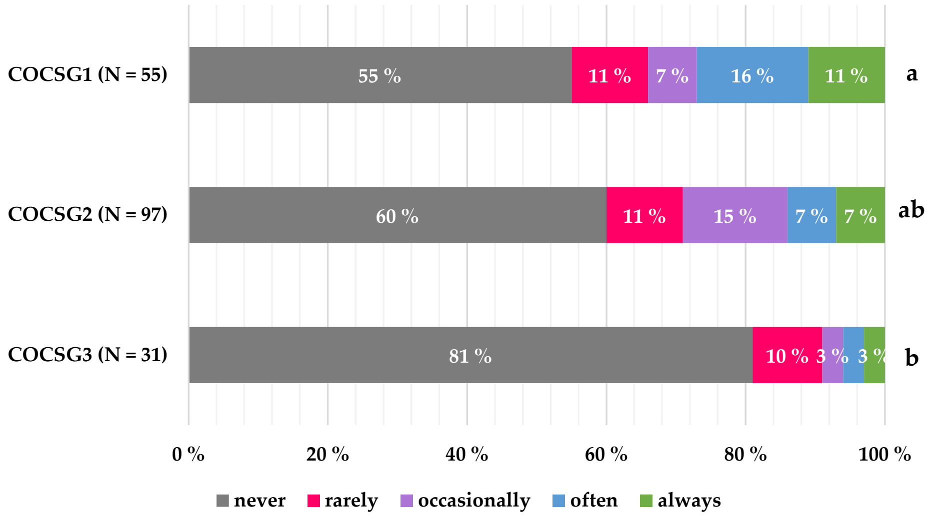


Figure 16. Results regarding adding milk to tea (N=183), illustrating group differences between combined oral chemesthetic sensitivity groups: COCSG1 (hyposensitive), COCSG2 (semi-sensitive), and COCSG3 (hypersensitive). Differences were studied using Kruskal–Wallis tests with pair-wise comparison (a and b).

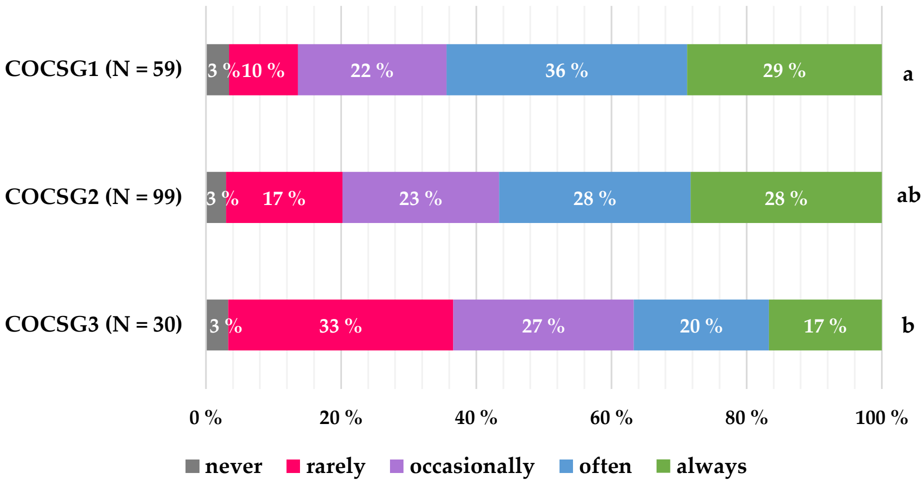


Figure 17. Results regarding eating fruits (*N*=188), illustrating group differences between combined oral chemesthetic sensitivity groups: COCSG1 (hyposensitive), COCSG2 (semi-sensitive), and COCSG3 (hypersensitive). Differences were studied using one-way ANOVA tests with Tukey's HSD *post-hoc* test (a and b).

Women showed similar connections. Hyposensitive women were more frequently 1) adding milk to coffee: 2.24 ± 1.53 ($H_{(2)}$=7.99, p<0.05, N=147) and 2) eating fruits: 3.93 ± 0.99 ($F_{(2)}$=3.50, p<0.05, N=149) than hypersensitive women: 1) 1.46 ± 1.03 and 2) 3.20 ± 1.12. In addition, hyposensitive men were less frequently adding ketchup to foods: 1.94 ± 0.68 ($F_{(1)}$=5.16, p<0.05, N=37) than more sensitive (S+H) men: 2.50 ± 0.80, respectively.

6. DISCUSSION

The research findings of this dissertation provide new insights into chemesthetic perception. The six predefined hypotheses were formulated based on the aims. The original data focused on human perception and influenced the choice of methods in this dissertation. In this section, each aim and hypothesis will be address in detail.

6.1. Chemesthetic perception varies and is connected to taste

The results indicate differences in chemesthetic sensitivity among individuals which is in line with Hypothesis 1: "*Individual differences exist*". To elaborate, individuals can be classified into different sensitivity groups in pungency, cooling, and astringency, and a combined sensitivity group. These results support earlier findings stating that individuals vary in sensitivity to chemesthetic perception (Dalton & Byrnes, 2016; Green, 1996; Monteleone et al., 2017). Classification of the hyposensitive, semi-sensitive, and hypersensitive groups was successfully executed using hierarchical clustering. Similar data segmenting methods have been used before to measure differences in taste sensitivity (Puputti et al. 2018). In consumer sensory projects, Euclidean distance with Ward's method is suggested as being a safe and valid choice for a clustering method, yet testing alternative clustering methods to fit the data is recommended (Gere 2023). Logically, prototypical chemesthetic sensations became more intense and clearer as the concentration increased. It is claimed that at low concentrations, chemesthetic components lack distinction (Green, 1996).

A positive correlation was discovered between oral chemesthetic sensitivity and taste sensitivity, supporting Hypothesis 2: "*Chemesthetic sensitivity is associated with taste sensitivity*". Chemesthetic quality-specific sensitivity groups had interactions among each other and with taste modalities. Ingredients that activate thermosensitive TRP channels have been suggested to indirectly interact with some taste modalities (Rhyu et al. 2021). For example, capsaicin has been shown to inhibit non-uniformly bitter taste in a sensory study using taste sample series mixed with capsaicin (Kapaun and Dando 2017). Pungency stimulation may enhance the perception of salty taste with a mutual inhibition of sour, sweet, and bitter taste (He et al. 2023). Furthermore, the combined oral chemesthetic sensitivity score ideally generalizes the sensitivity to chemesthesis, just as a taste sensitivity score ideally generalizes sensitivity to taste (Puputti et al. 2018). A positive correlation among different qualities was observed and sensitivity varies across different chemesthesis dimensions.

6.2. Role of personal explanatory factors in chemesthetic perception

The next steps focused on investigating potential factors that could explain individual differences. The regression models showed that sensitivity to chemesthesis can mainly be explained by biological factors age and gender. Age explained all the chemesthetic sensitivity group models, while gender explained only sensitivity to pungency (capsaicin). Increasing age predicted a lower sensitivity to pungency (capsaicin) and higher sensitivity to cooling (*l*-menthol) and astringency (aluminum ammonium sulfate). Results showed that men are less sensitive to pungency than women. These findings support Hypothesis 3: "*Age and gender are explanatory factors*". This research was honored with the Early Career Researcher Award for the best poster at EuroSense 2022: 10th European Conference on Sensory and Consumer Research conference on September 16, 2022 in Turku, Finland (**Appendix 2**).

Clinical evidence has shown that structural and functional decline of the somatosensory system can increase with aging (Shaffer and Harrison 2007). Capsaicin and *l*-menthol are compounds that activate somatosensory receptors channels: TRPV1 (capsaicin and high temperatures, ≥42°C) and TRPM8 (*l*-menthol and low temperatures, ≤30°C) that work in different temperature ranges (Takaishi et al. 2016). Since chemesthesis and physical temperature are linked to the same receptors, there might be interactions expected.

Our results support some of the earlier findings suggesting that capsaicin sensitivity differs between men and women (Byrnes and Hayes 2015). Additionally, similar gender differences have been discovered in a pain study focusing on the topical usage of capsaicin (Frot et al. 2004). They stated that women rated capsaicin induced pain higher, and men had more anxiety related to pain. However, the amount of study participants (N=20) was relatively small in that clinical research sample.

Chemesthetic sensitivity did not show connections to BMI and smoking status which does not support Hypothesis 4: "*BMI and smoking status are explanatory factors*". A previous study on taste sensitivity similarly found no connections between smoking status and taste sensitivity (Puputti et al. 2019a). Nevertheless, there were not many smokers in this study, which may impact the results. Associations between chemesthesis and both obesity and smoking have not previously been studied much. However, a COVID-19 study (Bhutani et al. 2022) revealed that obese individuals and those without obesity experienced a similar self-reported chemosensory loss and had the same symptoms caused by a COVID-19 infection. Tobacco smoke and nicotine elicit oral irritation and inhibit the sensory impact of capsaicin pain (e.g., Carstens & Carstens, 2022). They highlight that many nicotine-sensitive neurons respond to capsaicin and menthol cross-desensitizes nicotine-evoked oral irritation, impacting the flavor of tobacco products.

6.3. Chemesthesis is a part of food-related behavior

Consumption and recalled pleasantness of F&B-items had multidimensional interactions with chemesthetic sensitivity among all participants. Generally, the impacts revealed with MANOVA models were in line with PLS regression generated results. However, the connections varied depending on the studied chemesthetic dimension and the F&B-item. Thus, results are complex and demonstrate individual differences. Generally, differences between hyper- and hyposensitivity groups were the most interesting. In most cases, a higher sensitivity indicated lower consumption and recalled pleasantness ratings of F&B-items that have chemesthetic properties. These findings support Hypothesis 5: "*Consumption and recalled pleasantness are linked to sensitivity*". In addition, preliminary results showed stronger connections between chemesthetic sensitivity and food-related behavior among men rather than women. The stronger connections were discovered especially from F&B-items that belonged to the fatty-salty-sweet foods and alcoholic beverages categories. However, there were relatively few men in the groups, which highlights the need for more research to confirm this finding.

Nolden & Hayes (2017) state that infrequent consumers report more burning from capsaicin. Another study discovered that personality traits differ between men and women (Spinelli et al. 2018). In addition, a negative relationship between the intensity of capsaicin solutions and yearly intake of chili and pungent food was discovered for both men and women. In contrast, certain personality traits (sensation seeking and sensitivity to reward) were associated with the liking and intake of spicy foods differently in men and women (Byrnes and Hayes 2015). Sensation seeking was more strongly associated in women, and sensitivity to reward more in men.

A higher response to chemesthesis has been linked to the aversion and lower liking of alcoholic beverages (Nolden and Hayes 2015; Thibodeau et al. 2017; Cravero et al. 2020). Interestingly, taste sensitivity was not related to alcohol pleasantness or intake (Puputti et al., 2019). This highlights that chemesthesis is an important factor in the sensory experience of alcoholic beverages, especially with men participants. Strong astringency has been linked to aversion to berry juice (Laaksonen et al. 2013). Here, the connection between astringency and the liking of berries was not found. Since astringency is a complex sensation (Bajec and Pickering 2008), and response to astringency differs between metallic and polyphenolic compounds (Peleg et al. 1998; Dinnella et al. 2011), it is possible that polyphenolic induced astringency sensitivity would produce different results.

Cooling has been linked with the sensation of freshness, which is often present in products such as *breath mints* and *chewing gum* (Pringle 2016). Moreover, *l*-menthol can, in high concentrations, cause pungent stimuli that may explain associations with alcoholic beverages. Alcohol and carbonation have been linked to freshness in addition to pungent and tingly sensations (Klein 2019). To conclude, personality traits can contribute to the preferences and consumption of F&B.

Results showed a potential habit to mask chemesthetic sensations such as astringency and pungency. For example, adding sugar or milk to coffee and the increased usage of ketchup on foods can indicate masking behavior. A higher sensitivity to astringency increased the habit of adding ketchup to foods. In the case of pungency, a higher sensitivity was linked with a more frequent habit of adding milk to coffee. In contrast, some complexity against the logic of masking behavior was also detected in the habits of adding milk and sweet compounds to tea. For example, a higher cooling sensitivity was linked with the less frequent habit of adding milk to tea. Despite the complexity, most of the logical findings are in line with Hypothesis 6. "*Dietary habits are linked to sensitivity*". In addition, preliminary research showed that chemesthetic sensitivity had stronger connections to dietary habits among men participants, which should be confirmed in the future with more balanced data.

A similar kind of masking behavior was observed in taste research, especially in the case of bitter taste (Puputti et al. 2019b). Participants who are more sensitive may perceive chemesthetic ingredients in foods more strongly and end up masking unpleasant stimuli. Fatty, sweet, and creamy properties have been linked with the masking of unpleasant flavor properties such as astringency and bitterness in several earlier studies (Lyman and Green 1990; De Wijk et al. 2003; Bajec and Pickering 2008; Laaksonen 2011; Törnwall 2013).

6.4. Strengths and limitations

Interpretation of the results of this chemesthesis study needs to acknowledge few aspects that impact the research set up. This study is part of a larger research program and is supported by previous doctoral research on taste sensitivity that utilized the same data, and thus, shares similar study-related limitations (Puputti 2020).

The participants were a heterogenous group with unbalanced background factors including gender and self-reported information such as body weight and height for BMI. Women, lean, highly educated, and non-smokers were a majority in the data. Although women have been more willing to participate, gender-focused results should be confirmed with more balanced data in future research. However, we included all the volunteer men that were willing to participate to this study. Thus, these results must be viewed and interpreted carefully as preliminary results, especially in the case of men participants since there were relatively fewer of them than women. In the future, the PLS regression method can be used to study gender data separately, which may reveal multidimensional connections.

Although information concerning personality traits was included in the original data, they were excluded from this dissertation to maintain a focus on the study aims that allow for comparison between chemesthetic and previously studied taste. This study was large-scaled and, in most cases, good-sized reference groups were generated. These results can be compared to other chemosensory research.

The study participants were not trained and equaled as consumers. However, they were given written and verbal advice and an introduction to the chemesthetic samples to prevent the element of surprise. The scales used were structured with written anchors to make them understandable and to avoid scale-use bias. Due to the untrained participants, reference samples were not used. The researchers that created and collected the sensory data planned the study to prevent fatigue and to keep participants alert since test days were approximately 120 minutes long. A visual analogue scale (VAS) was selected because the general Labeled Magnitude Scale (gLMS) would have not fit well for the low concentration chemesthetic samples. The concentrations were carefully selected based on previous experiences and pre-testing was conducted to prevent a ceiling effect and unpleasant experience.

Chemesthetic samples were prepared by using prototypic compounds known to activate chemesthetic perception. Results would have been different with other compounds. Measuring the overall intensity was seen to be the best method. The compounds were tested in several different concentrations. The multiple samples tested at different concentrations increase the validity of these findings and help in understanding the impact of the results better.

Hierarchical clustering was used exploratively to find the most suitable chemesthetic sensitivity clusters. This method was seen to be valid based on previous findings and the literature (Puputti et al. 2018; Gere 2023). Food-related behavior data included F&B-items that were classified based on previous taste research (Puputti et al. 2019b). The selected food-related behavior variables such as coffee can have multiple alternative meanings (e.g., *black coffee*, *coffee with milk*, *café latte*, and *frappuccino*), which may impact the results. Although the questionnaire was not validated, it was structured to match Nordic food culture. For example, all of the F&B-items can be found commonly in Finnish grocery stores.

Comparison of the results to other research was challenging due to the complexity of the data and specific study aims. Research that explores these kinds of oral chemesthesis dimensions with a wide set of food-behavior factors is lacking.

6.5. Future directions

This chemesthesis-focused research can be developed further. For example, if wanting to confirm gender differences, the number of participants should be balanced in further chemesthesis research. In addition to pungency, cooling, and astringency, research could be extended to study other chemesthetic dimensions such as numbness, pain, tingling, and sharpness (**Figure 1**). This would provide wider aspects in the behavioral context in general. However, collecting large-scale sensory data takes an enormous amount of effort that should be noted in further research.

Ethanol is a multidimensional compound. Thus, it would be interesting to investigate individuality regarding the overall intensity of ethanol at different concentrations and the variation of chemesthetic-quality recognition using qualities listed in **Figure 1**. This could be studied with the Check-All-That-Apply (CATA) method to discover variation among qualities, or with the more challenging Rate-All-That-Apply (RATA) method that would provide new insights about the profile of sensations. In addition, the hedonic response of ethanol samples could be studied in sensory laboratory conditions. These results could be reflected regarding the pleasantness and consumption ratings of different alcoholic beverages linked to the findings of this dissertation.

Chemesthesis should be studied also with longitude sensory tests. For example, to understand the role of chemesthetic sensitivity as risk factor in alcoholism and alcohol consumption, it would be useful to have follow-up studies of ethanol sensory testing focusing on sensitivity and pleasantness with young adults. Such studies may contribute to developing new tools for preventing alcohol-related health problems. However, a sensory study linked to ethanol is challenging due to limiting factors: pregnancy, alcoholism, underage participants, and ethanol also being carcinogenic. Asking about alcohol consumption can also be a sensitive subject, and some individuals may hide their true behavior related to alcohol consumption, which may cause bias.

In addition to taste and chemesthesis, also smell, texture, and color perception have been studied with these same study participants in the FoodTaste Finland Research program. Studying associations with smell could enhance our knowledge of flavor perception and its influence on food-related behavior. On the other hand, the physical properties of foods (e.g., texture) can impact food-related behavior such as liking plant-based products (Greis et al. 2023). Hence, investigating interactions between chemesthesis and physical somatosensory dimensions such as texture is important because the food experience is multisensory.

Since Finland is one of the highest coffee-consuming countries, future research could also focus on studying the impact of sensitivity related masking behavior using samples made from different coffee types and with selection of different masking agents (e.g., milk, cream, oat-milk, almond-milk, sugar, and sweeteners), which is linked to the findings on dietary habits of this dissertation.

7. CONCLUSIONS

Oral chemesthetic perception is highly individual. Individuals can be classified into distinct groups based on their sensitivity and recognition levels. Prototypic compounds for pungency (capsaicin), cooling (*l*-menthol), and astringency (aluminum ammonium sulfate) are valid chemesthetic ingredients. A positive association between chemesthesis and taste was observed. The main factors explaining chemesthetic perception appear to be gender, age, and recognition skills. Women were found to be more sensitive to pungency than men, and increasing age was associated with lower sensitivity to pungency. Increasing age was associated with higher sensitivity in the case of cooling and astringency. Higher recognition ratings predicted higher sensitivity in each dimension. Importantly, some individuals had an opposite rating result than these predictions. These results can only be indicators, and we highlight that chemesthetic perception is as subjective as taste perception.

Chemesthetic sensitivity was linked to both the consumption and recalled pleasantness of certain F&B-items familiar to Nordic food culture. Additionally, sensitivity was connected to some dietary habits that can indicate the masking behavior of unpleasantly perceived flavors. These connections seem to be chemesthetic quality and F&B-item specific. The individuality of chemesthetic perception not only influences the consumption and recalled pleasantness of foods containing chemesthetic ingredients, but also broader dietary patterns. Preliminary results of this research raised concerns regarding men's food-related behavior and possible unhealthy eating and drinking habits that need to be confirmed in future research with a more balanced data set.

The complexity and individuality of chemesthetic perception highlights the need for new methods in chemesthesis sensory research in food and other industries. In the future, the relationship between chemesthesis and the pleasantness of F&B can be studied using food sensory samples. The novel chemesthesis score models can be applied in product development processes that target development of sustainable and healthier food solutions, especially when dealing with plant-based material, where chemesthetic ingredients are often present. This doctoral research promotes the subjectivity of food sensory experience and provides new insights into chemesthetic perception, helping to create more sustainable solutions impacting the food chain and health.

REFERENCES

Ager AL, Borms D, Deschepper L, Dhooghe R, Dijkhuis J, Roy J-S, Cools A (2020) Proprioception: How is it affected by shoulder pain? A systematic review. Journal of Hand Therapy 33(4):507–516. https://doi.org/10.1016/j.jht.2019.06.002

Algahtani SN, Alzarroug AF, Alghamdi HK, Algahtani HK, Alsywina NB, Bin Abdulrahman KA (2022) Investigation on the Factors Associated with the Persistence of Anosmia and Ageusia in Saudi COVID-19 Patients. IJERPH 19(3):1047. https://doi.org/10.3390/ijerph19031047

Alhajj M, Babos M (2023) Physiology, Salivation. In: StatPearls. https://www.ncbi.nlm.nih.gov/books/NBK542251/

Baggesen DL (2024) Assessment of three noodle products based on measurements of total capsaicin content in chilli sauce

Bajec MR, Pickering GJ (2008) Astringency: Mechanisms and Perception. Critical Reviews in Food Science and Nutrition 48(9):858–875. https://doi.org/10.1080/10408390701724223

Beltrán LR, Dawid C, Beltrán M, Gisselmann G, Degenhardt K, Mathie K, Hofmann T, Hatt H (2013) The pungent substances piperine, capsaicin, 6-gingerol and polygodial inhibit the human two-pore domain potassium channels TASK-1, TASK-3 and TRESK. Front Pharmacol 4. https://doi.org/10.3389/fphar.2013.00141

Benemei S, Fusi C, Trevisan G, Geppetti P (2014) The TRPA1 channel in migraine mechanism and treatment. British J Pharmacology 171(10):2552–2567. https://doi.org/10.1111/bph.12512

Bhutani S, Coppin G, Veldhuizen MG, Parma V, Joseph PV (2022) COVID-19 related chemosensory changes in individuals with self-reported obesity. Rhin 0(0):0–0. https://doi.org/10.4193/Rhin21.351

Blomhoff R, Andersen R, Arnesen EK, Christensen JJ, Eneroth H, Erkkola M, Gudanaviciene I, Halldórsson ÞI, Høyer-Lund A, Lemming EW, Meltzer HM, Pitsi T, Siksna I, Þórsdóttir I, Trolle E (2023) Nordic Nutrition Recommendations 2023. Nordic Council of Ministers

Byrnes NK, Hayes JE (2015) Gender differences in the influence of personality traits on spicy food liking and intake. Food Quality and Preference 42:12–19. https://doi.org/10.1016/j.foodqual.2015.01.002

Byrnes NK, Hayes JE (2013) Personality factors predict spicy food liking and intake. Food Quality and Preference 28(1):213–221. https://doi.org/10.1016/j.foodqual.2012.09.008

Carstens E (2016) Overview of chemesthesis with a look to the future. In: McDonald ST, Bolliet DA, Hayes JE (eds) Chemesthesis, 1st edn. Wiley, pp 268–285

Carstens E, Carstens MI (2022) Sensory Effects of Nicotine and Tobacco. Nicotine & Tobacco Research 24(3):306–315. https://doi.org/10.1093/ntr/ntab086

Caterina MJ, Schumacher MA, Tominaga M, Rosen TA, Levine JD, Julius D (1997) The capsaicin receptor: a heat-activated ion channel in the pain pathway. Nature 389(6653):816–824. https://doi.org/10.1038/39807

Cayeux I, Saint-Léger C, Starkenmann C (2023) Trigeminal Sensations to enhance and enrich flavor perception - Sensory Approaches. Clinical Nutrition Open Science 47:64–73. https://doi.org/10.1016/j.nutos.2022.11.007

Cecchetto C, Di Pizio A, Genovese F, Calcinoni O, Macchi A, Dunkel A, Ohla K, Spinelli S, Farruggia MC, Joseph PV, Menini A, Cantone E, Dinnella C, Cecchini MP, D'Errico A, Mucignat-Caretta C, Parma V, Dibattista M (2021) Assessing the extent and timing of chemosensory impairments during COVID-19 pandemic. Sci Rep 11(1):17504. https://doi.org/10.1038/s41598-021-96987-0

Chéruel F, Jarlier M, Sancho-Garnier H (2017) Effect of cigarette smoke on gustatory sensitivity, evaluation of the deficit and of the recovery time-course after smoking cessation. Tob Induced Dis 15(1):15. https://doi.org/10.1186/s12971-017-0120-4

Chopra K, Tiwari V (2012) Alcoholic neuropathy: possible mechanisms and future treatment possibilities. Brit J Clinical Pharma 73(3):348–362. https://doi.org/10.1111/j.1365-2125.2011.04111.x

Clark L, Hagelin J, Werner S (2015) The Chemical Senses in Birds. In: Sturkie's Avian Physiology. Elsevier, pp 89–111

Corrales M, Fernández A, Han JH (2014) Antimicrobial Packaging Systems. In: Innovations in Food Packaging. Elsevier, pp 133–170

Cravero MC, Laureati M, Spinelli S, Bonello F, Monteleone E, Proserpio C, Lottero MR, Pagliarini E, Dinnella C (2020) Profiling Individual Differences in Alcoholic Beverage Preference and Consumption: New Insights from a Large-Scale Study. Foods 9(8):1131. https://doi.org/10.3390/foods9081131

Dalton P, Byrnes N (2016) Psychology of chemesthesis – why would anyone want to be in pain? In: McDonald ST, Bolliet DA, Hayes JE (eds) Chemesthesis, 1st edn. Wiley, pp 8–31

De Wijk RA, Van Gemert LJ, Terpstra MEJ, Wilkinson CL (2003) Texture of semi-solids; sensory and instrumental measurements on vanilla custard desserts. Food Quality and Preference 14(4):305–317. https://doi.org/10.1016/S0950-3293(02)00107-6

Dessirier J-M, O'Mahony M, Iodi-Carstens M, Yao E, Carstens E (2001) Oral irritation by sodium chloride: sensitization, self-desensitization, and cross-sensitization to capsaicin. Physiology & Behavior 72(3):317–324. https://doi.org/10.1016/S0031-9384(00)00412-1

Di Stasio D (2016) An overview of burning mouth syndrome. Front Biosci 8(1):213–218. https://doi.org/10.2741/e762

Dinakar P, Stillman AM (2016) Pathogenesis of Pain. Seminars in Pediatric Neurology 23(3):201–208. https://doi.org/10.1016/j.spen.2016.10.003

Dinnella C, Recchia A, Fia G, Bertuccioli M, Monteleone E (2009) Saliva Characteristics and Individual Sensitivity to Phenolic Astringent Stimuli. Chemical Senses 34(4):295–304. https://doi.org/10.1093/chemse/bjp003

Dinnella C, Recchia A, Tuorila H, Monteleone E (2011) Individual astringency responsiveness affects the acceptance of phenol-rich foods. Appetite 56(3):633–642. https://doi.org/10.1016/j.appet.2011.02.017

Elmas C, Gezer C (2022) Capsaicin and Its Effects on Body Weight. Journal of the American Nutrition Association 41(8):831–839. https://doi.org/10.1080/07315724.2021.1962771

Famuyide A, Massoud TF, Moonis G (2022) Oral Cavity and Salivary Glands Anatomy. Neuroimaging Clinics of North America 32(4):777–790. https://doi.org/10.1016/j.nic.2022.07.021

Fattori V, Hohmann M, Rossaneis A, Pinho-Ribeiro F, Verri W (2016) Capsaicin: Current Understanding of Its Mechanisms and Therapy of Pain and Other Pre-Clinical and Clinical Uses. Molecules 21(7):844. https://doi.org/10.3390/molecules21070844

Filiou R-P, Lepore F, Bryant B, Lundstrom JN, Frasnelli J (2015) Perception of Trigeminal Mixtures. Chemical Senses 40(1):61–69. https://doi.org/10.1093/chemse/bju064

Finger TE, Simon SA (2000) Cell Biology of Taste Epithelium. In: Finger TE, Silver WL, Restrepo D (eds) The Neurobiology of Taste and Smell, 2nd edn. Wiley-Liss, Inc., New York, pp 287–314

Finnish Food Authority (2024a) E524 - Alumiiniammoniumsulfaatti. https://www.ruokavirasto.fi/elintarvikkeet/ohjeita-kuluttajille/e-kooditlisaaineet/e-koodit/e523/

Finnish Food Authority (2024b) Erittäin tulisten ruokien suuren määrän nauttiminen kerralla ei ole järkevää. In: Ruokavirasto.fi. https://www.ruokavirasto.fi/elintarvikkeet/ohjeita-kuluttajille/uutisia-kuluttajille/erittain-tulisten-ruokien-suuren-maaran-nauttiminen-kerralla-ei-ole-jarkevaa/

Forde CG, Delahunty CM (2004) Understanding the role cross-modal sensory interactions play in food acceptability in younger and older consumers. Food Quality and Preference 15(7–8):715–727. https://doi.org/10.1016/j.foodqual.2003.12.008

Frot M, Feine JS, Bushnell CM (2004) Sex differences in pain perception and anxiety. A psychophysical study with topical capsaicin. Pain 108(3):230–236. https://doi.org/10.1016/j.pain.2003.11.017

Gaiser J, Hayes JE (2024) Fat, protein, and temperature each contribute to reductions in capsaicin oral burn. Journal of Food Science :1750-3841.17221. https://doi.org/10.1111/1750-3841.17221

Gaiser J, Hayes JE (2023) More than fat – Proteins in dairy and plant milks contribute to the reduction of oral burn from capsaicin. Food Quality and Preference 112:105041. https://doi.org/10.1016/j.foodqual.2023.105041

Gere A (2023) Recommendations for validating hierarchical clustering in consumer sensory projects. Current Research in Food Science 6:100522. https://doi.org/10.1016/j.crfs.2023.100522

Gilmore MM, Green BG (1993) Sensory irritation and taste produced by NaCl and citric acid: effects of capsaicin desensitization. Chem Senses 18(3):257–272. https://doi.org/10.1093/chemse/18.3.257

Gray K, Yep L, Eilerman R (2008) Salt enhancement. US-Patent:200880311266

Green B, Alvarezreeves M, George P, Akirav C (2005) Chemesthesis and taste: Evidence of independent processing of sensation intensity. Physiology & Behavior 86(4):526–537. https://doi.org/10.1016/j.physbeh.2005.08.038

Green B, Hayes J (2003) Capsaicin as a probe of the relationship between bitter taste and chemesthesis. Physiology & Behavior 79(4–5):811–821. https://doi.org/10.1016/S0031-9384(03)00213-0

Green BG (2012) Chemesthesis and the Chemical Senses as Components of a “Chemofensor Complex.” Chemical Senses 37(3):201–206. https://doi.org/10.1093/chemse/bjr119

Green BG (2003) Stimulation of Bitterness by Capsaicin and Menthol: Differences Between Lingual Areas Innervated by the Glossopharyngeal and Chorda Tympani Nerves. Chemical Senses 28(1):45–55. https://doi.org/10.1093/chemse/28.1.45

Green BG (1986) Sensory interactions between capsaicin and temperature in the oral cavity. Chem Senses 11(3):371–382. https://doi.org/10.1093/chemse/11.3.371

Green BG (1985) Menthol modulates oral sensations of warmth and cold. Physiology & Behavior 35(3):427–434. https://doi.org/10.1016/0031-9384(85)90319-1

Green BG (1996) Chemesthesis: Pungency as a component of flavor. Trends in Food Science & Technology 7(12):415–420. https://doi.org/10.1016/S0924-2244(96)10043-1

Greis M, Nolden AA, Kinchla AJ, Puputti S, Seppä L, Sandell M (2023) What if plant-based yogurts were like dairy yogurts? Texture perception and liking of plant-based yogurts among US and Finnish consumers. Food Quality and Preference 107:104848. https://doi.org/10.1016/j.foodqual.2023.104848

Gwartney E, Heymann H (1995) THE TEMPORAL PERCEPTION OF MENTHOL [1]. Journal of Sensory Studies 10(4):393–400. https://doi.org/10.1111/j.1745-459X.1995.tb00028.x

Haley H, McDonald ST (2016) Spice and herb extracts with chemesthetic effects. In: McDonald ST, Bolliet DA, Hayes JE (eds) Chemesthesis, 1st edn. Wiley, pp 32–47

Hammi C, Yeung B (2024) Neuropathy. In: StatPearls. StatPearls Publishing, Treasure Island (FL)

Hayes JE (2020) Influence of Sensation and Liking on Eating and Drinking. In: Meiselman HL (ed) Handbook of Eating and Drinking. Springer International Publishing, Cham, pp 131–155

Hayes JE (2016) Types of chemesthesis I. Pungency and burn: historical perspectives, word usage, and temporal characteristics. In: McDonald ST, Bolliet DA, Hayes JE (eds) Chemesthesis, 1st edn. Wiley, pp 92–105

Hayman M, Kam PCA (2008) Capsaicin: A review of its pharmacology and clinical applications. Current Anaesthesia & Critical Care 19(5–6):338–343. https://doi.org/10.1016/j.cacc.2008.07.003

He W, Liang L, Zhang Y (2023) Pungency Perception and the Interaction with Basic Taste Sensations: An Overview. Foods 12(12):2317. https://doi.org/10.3390/foods12122317

Hoppu U, Knaapila A, Laaksonen O, Sandell M (2016) Genetic basis of flavor sensitivity and food preferences. In: Flavor. Elsevier, pp 203–227

Hunter SR, Beatty C, Dalton PH (2023) More spice, less salt: How capsaicin affects liking for and perceived saltiness of foods in people with smell loss. Appetite 190:107032. https://doi.org/10.1016/j.appet.2023.107032

Ilie M, Caruntu C, Tampa M, Georgescu S-R, Matei C, Negrei C, Ion R-M, Constantin C, Neagu M, Boda D (2019) Capsaicin: Physicochemical properties, cutaneous reactions and potential applications in painful and inflammatory conditions (Review). Exp Ther Med. https://doi.org/10.3892/etm.2019.7513

Jöbstl E, O'Connell J, Fairclough JPA, Williamson MP (2004) Molecular Model for Astringency Produced by Polyphenol/Protein Interactions. Biomacromolecules 5(3):942–949. https://doi.org/10.1021/bm0345110

Jordt S-E, Bautista DM, Chuang H, McKemy DD, Zygmunt PM, Högestätt ED, Meng ID, Julius D (2004) Mustard oils and cannabinoids excite sensory nerve fibres through the TRP channel ANKTM1. Nature 427(6971):260–265. https://doi.org/10.1038/nature02282

Jordt S-E, Julius D (2002) Molecular Basis for Species-Specific Sensitivity to "Hot" Chili Peppers. Cell 108(3):421–430. https://doi.org/10.1016/S0092-8674(02)00637-2

Kapaun CL, Dando R (2017) Deconvoluting physical and chemical heat: Temperature and spiciness influence flavor differently. Physiology & Behavior 170:54–61. https://doi.org/10.1016/j.physbeh.2016.12.015

Klein AH (2019) The orotrigeminal system. In: Handbook of Clinical Neurology. Elsevier, pp 205–216

Koskinen S, Kälviäinen N, Tuorila H (2003) Perception of chemosensory stimuli and related responses to flavored yogurts in the young and elderly. Food Quality and Preference 14(8):623–635. https://doi.org/10.1016/S0950-3293(02)00187-8

Kurogi M, Kawai Y, Nagatomo K, Tateyama M, Kubo Y, Saitoh O (2015) Auto-oxidation Products of Epigallocatechin Gallate Activate TRPA1 and TRPV1 in Sensory Neurons. Chemical Senses 40(1):27–46. https://doi.org/10.1093/chemse/bju057

Laaksonen O (2011) Astringent Food Compounds and Their Interactions with Taste Properties - Academic Dissertation. University of Turku, Turku, Finland

Laaksonen O, Ahola J, Sandell M (2013) Explaining and predicting individually experienced liking of berry fractions by the hTAS2R38 taste receptor genotype. Appetite 61:85–96. https://doi.org/10.1016/j.appet.2012.10.023

Labbe D, Gilbert F, Antille N, Martin N (2009) Sensory determinants of refreshing. Food Quality and Preference 20(2):100–109. https://doi.org/10.1016/j.foodqual.2007.09.001

Labbe D, Martin N, Le Coutre J, Hudry J (2011) Impact of refreshing perception on mood, cognitive performance and brain oscillations: An exploratory study. Food Quality and Preference 22(1):92–100. https://doi.org/10.1016/j.foodqual.2010.08.002

Lawless HT, Heymann H (2010) Physiological and Psychological Foundations of Sensory Function. In: Sensory Evaluation of Food. Springer New York, New York, NY, pp 19–56

Lawless HT, Stevens DA (1988) Responses by humans to oral chemical irritants as a function of locus of stimulation. Perception & Psychophysics 43(1):72–78. https://doi.org/10.3758/BF03208975

Leblanc S, McCormack K, Casey M (2024) Teen who ate spicy tortilla chip died of high chile consumption and had a heart defect, autops says. In: Teen who ate spicy tortilla chip died of high chile consumption and had a heart defect, autops says. https://apnews.com/article/paqui-spicy-chip-challenge-death-autopsy-f81c220c549ec497bcc626dec4fc2be4

Lee CB, Lawless HT (1991) Time-course of astringent sensations. Chem Senses 16(3):225–238. https://doi.org/10.1093/chemse/16.3.225

Levy DT, Meza R, Yuan Z, Li Y, Cadham C, Sanchez-Romero LM, Travis N, Knoll M, Liber AC, Mistry R, Hirschtick JL, Fleischer NL, Skolnick S, Brouwer AF, Douglas C, Jeon J, Cook S, Warner KE (2023) Public health impact of a US ban on menthol in cigarettes and cigars: a simulation study. Tob Control 32(e1):e37–e44. https://doi.org/10.1136/tobaccocontrol-2021-056604

Loss CR, Bouzari A (2016) On food and chemesthesis – food science and culinary perspectives. In: McDonald ST, Bolliet DA, Hayes JE (eds) Chemesthesis, 1st edn. Wiley, pp 250–267

Lundström JN, Boesveldt S, Albrecht J (2011) Central Processing of the Chemical Senses: An Overview. ACS Chem Neurosci 2(1):5–16. https://doi.org/10.1021/cn1000843

Lyman BJ, Green BG (1990) Oral astringency: effects of repeated exposure and interactions with sweeteners. Chem Senses 15(2):151–164. https://doi.org/10.1093/chemse/15.2.151

Lyu C, Schijvens D, Hayes JE, Stieger M (2021) Capsaicin burn increases thickness discrimination thresholds independently of chronic chili intake. Food Research International 149:110702. https://doi.org/10.1016/j.foodres.2021.110702

Lyu C, Vonk M, Hayes JE, Chen J, Forde CG, Stieger M (2023) The heat is on: Consumers modify their oral processing behavior when eating spicy foods. Current Research in Food Science 7:100597. https://doi.org/10.1016/j.crfs.2023.100597

Mattes RD, Ludy M (2016) Chemesthesis and health. In: McDonald ST, Bolliet DA, Hayes JE (eds) Chemesthesis, 1st edn. Wiley, pp 227–249

McKemy DD, Neuhausser WM, Julius D (2002) Identification of a cold receptor reveals a general role for TRP channels in thermosensation. Nature 416(6876):52–58. https://doi.org/10.1038/nature719

Monteleone E, Spinelli S, Dinnella C, Endrizzi I, Laureati M, Pagliarini E, Sinesio F, Gasperi F, Torri L, Aprea E, Bailetti LI, Bendini A, Braghieri A, Cattaneo C, Cliceri D, Condelli N, Cravero MC, Del Caro A, Di Monaco R, Drago S, Favotto S, Fusi R, Galassi L, Gallina Toschi T, Garavaldi A, Gasparini P, Gatti E, Masi C, Mazzaglia A, Moneta E, Piasentier E, Piochi M, Pirastu N, Predieri S, Robino A, Russo F, Tesini F (2017) Exploring influences on food choice in a large population sample: The Italian Taste project. Food Quality and Preference 59:123–140. https://doi.org/10.1016/j.foodqual.2017.02.013

National Center for Biotechnology Information (2024a) PubChem Compound Sumary for CID 1548943 Capsaicin. https://pubchem.ncbi.nlm.nih.gov/compound/Capsaicin

National Center for Biotechnology Information (2024b) PubChem Compound Summary for CID 16666, l-Menthol. https://pubchem.ncbi.nlm.nih.gov/compound/l-Menthol

National Center for Biotechnology Information (2024c) PubChem Compound Summary for CID 3032540, Aluminum ammonium sulfate. https://pubchem.ncbi.nlm.nih.gov/compound/Aluminum-ammonium-sulfate

Nolden AA, Hayes JE (2017) Perceptual and affective responses to sampled capsaicin differ by reported intake. Food Quality and Preference 55:26–34. https://doi.org/10.1016/j.foodqual.2016.08.003

Nolden AA, Hayes JE (2015) Perceptual Qualities of Ethanol Depend on Concentration, and Variation in These Percepts Associates with Drinking Frequency. Chem Percept 8(3):149–157. https://doi.org/10.1007/s12078-015-9196-5

Nolden AA, Lenart G, Hayes JE (2019) Putting out the fire – Efficacy of common beverages in reducing oral burn from capsaicin. Physiology & Behavior 208:112557. https://doi.org/10.1016/j.physbeh.2019.05.018

Nolden AA, Lenart G, Spielman AI, Hayes JE (2024) Inducible desensitization to capsaicin with repeated low-dose exposure in human volunteers. Physiology & Behavior 275:114447. https://doi.org/10.1016/j.physbeh.2023.114447

Nolden AA, McGeary JE, Hayes JE (2016) Differential bitterness in capsaicin, piperine, and ethanol associates with polymorphisms in multiple bitter taste receptor genes. Physiology & Behavior 156:117–127. https://doi.org/10.1016/j.physbeh.2016.01.017

Parma V, Ohla K, Veldhuizen MG, Niv MY, Kelly CE, Bakke AJ, Cooper KW, Bouysset C, Pirastu N, Dibattista M, Kaur R, Liuzza MT, Pepino MY, Schöpf V, Pereda-Loth V, Olsson SB, Gerkin RC, Rohlfs Domínguez P, Albayay J, Farruggia MC, Bhutani S, Fjaeldstad AW, Kumar R, Menini A, Bensafi M, Sandell M, Konstantinidis I, Di Pizio A, Genovese F, Öztürk L, Thomas-Danguin T, Frasnelli J, Boesveldt S, Saatci Ö, Saraiva LR, Lin C, Golebiowski J, Hwang L-D, Ozdener MH, Guàrdia MD, Laudamiel C, Ritchie M, Havlícek J, Pierron D, Roura E, Navarro M, Nolden AA, Lim J, Whitcroft KL, Colquitt LR, Ferdenzi C, Brindha EV, Altundag A, Macchi A, Nunez-Parra A, Patel ZM, Fiorucci S, Philpott CM, Smith BC, Lundström JN, Mucignat C, Parker JK, Van Den Brink M, Schmuker M, Fischmeister FPS, Heinbockel T, Shields VDC, Faraji F, Santamaría E, Fredborg WEA, Morini G, Olofsson JK, Jalessi M, Karni N, D'Errico A, Alizadeh R, Pellegrino R, Meyer P, Huart C, Chen B, Soler GM, Alwashahi MK, Welge-Lüssen A, Freiherr J, De Groot JHB, Klein

H, Okamoto M, Singh PB, Hsieh JW, GCCR Group Author, Abdulrahman O, Dalton P, Yan CH, Voznessenskaya VV, Chen J, Sell EA, Walsh-Messinger J, Archer NS, Koyama S, Deary V, Roberts SC, Yanık H, Albayrak S, Nováková LM, Croijmans I, Mazal PP, Moein ST, Margulis E, Mignot C, Mariño S, Georgiev D, Kaushik PK, Malnic B, Wang H, Seyed-Allaei S, Yoluk N, Razzaghi-Asl S, Justice JM, Restrepo D, Reed DR, Hummel T, Munger SD, Hayes JE (2020) More Than Smell—COVID-19 Is Associated With Severe Impairment of Smell, Taste, and Chemesthesis. Chemical Senses 45(7):609–622. https://doi.org/10.1093/chemse/bjaa041

Peier AM, Moqrich A, Hergarden AC, Reeve AJ, Andersson DA, Story GM, Earley TJ, Dragoni I, McIntyre P, Bevan S, Patapoutian A (2002) A TRP Channel that Senses Cold Stimuli and Menthol. Cell 108(5):705–715. https://doi.org/10.1016/S0092-8674(02)00652-9

Peleg H, Bodine KK, Noble AC (1998) The Influence of Acid on Astringency of Alum and Phenolic Compounds. Chemical Senses 23(3):371–378. https://doi.org/10.1093/chemse/23.3.371

Pellegrino R, Luckett CR (2019) The effect of odor and color on chemical cooling. Food Quality and Preference 75:118–123. https://doi.org/10.1016/j.foodqual.2019.03.002

Piochi M, Cabrino G, Morini G, Torri L (2020) Individual differences in the perception of orthonasal irritation induced by food. Appetite 144:104460. https://doi.org/10.1016/j.appet.2019.104460

Piochi M, Dinnella C, Spinelli S, Monteleone E, Torri L (2021) Individual differences in responsiveness to oral sensations and odours with chemesthetic activity: Relationships between sensory modalities and impact on the hedonic response. Food Quality and Preference 88:104112. https://doi.org/10.1016/j.foodqual.2020.104112

Prescott J (1995) Effects of oral chemical irritation on tastes and flavors in frequent and infrequent users of chili. Physiology & Behavior 58(6):1117–1127. https://doi.org/10.1016/0031-9384(95)02052-7

Prescott J, Stevenson RJ (1995) Pungency in food perception and preference. Food Reviews International 11(4):665–698. https://doi.org/10.1080/87559129509541064

Prescott J, Swain-Campbell N (2000) Responses to Repeated Oral Irritation by Capsaicin, Cinnamaldehyde and Ethanol in PROP Tasters and Non-tasters. Chemical Senses 25(3):239–246. https://doi.org/10.1093/chemse/25.3.239

Pringle S (2016) Types of chemesthesis II: Cooling. In: McDonald ST, Bolliet DA, Hayes JE (eds) Chemesthesis, 1st edn. Wiley, pp 106–133

Puputti S (2020) Individual Differences in Taste Perception - Focus on Food-related Behavior. Dissertation, University of Turku, Faculty of Medicine

Puputti S, Aisala H, Hoppu U, Sandell M (2018) Multidimensional measurement of individual differences in taste perception. Food Quality and Preference 65:10–17. https://doi.org/10.1016/j.foodqual.2017.12.006

Puputti S, Aisala H, Hoppu U, Sandell M (2019a) Factors explaining individual differences in taste sensitivity and taste modality recognition among Finnish adults. Journal of Sensory Studies 34(4):e12506. https://doi.org/10.1111/joss.12506

Puputti S, Hoppu U, Sandell M (2019b) Taste Sensitivity is Associated with Food Consumption Behavior but not with Recalled Pleasantness. Foods 8(10):444. https://doi.org/10.3390/foods8100444

Rhyu M-R, Kim Y, Lyall V (2021) Interactions between Chemesthesis and Taste: Role of TRPA1 and TRPV1. IJMS 22(7):3360. https://doi.org/10.3390/ijms22073360

Riantiningtyas RR, Valenti A, Dougkas A, Bredie WLP, Kwiecien C, Bruyas A, Giboreau A, Carrouel F (2023) Oral somatosensory alterations and salivary dysfunction in head and neck cancer patients. Support Care Cancer 31(11):627. https://doi.org/10.1007/s00520-023-08086-7

Riera CE, Vogel H, Simon SA, Coutre JL (2007) Artificial sweeteners and salts producing a metallic taste sensation activate TRPV1 receptors. American Journal of Physiology-Regulatory, Integrative and Comparative Physiology 293(2):R626–R634. https://doi.org/10.1152/ajpregu.00286.2007

Risso D, Drayna D, Morini G (2020) Alteration, Reduction and Taste Loss: Main Causes and Potential Implications on Dietary Habits. Nutrients 12(11):3284. https://doi.org/10.3390/nu12113284

Roukka S, Puputti S, Aisala H, Hoppu U, Seppä L, Sandell M (2023) Factors explaining individual differences in the oral perception of capsaicin, *l* - MENTHOL , and aluminum ammonium sulfate. Clinical Translational Sci 16(10):1815–1827. https://doi.org/10.1111/cts.13587

Roukka S, Puputti S, Aisala H, Hoppu U, Seppä L, Sandell MA (2021) The Individual Differences in the Perception of Oral Chemesthesis Are Linked to Taste Sensitivity. Foods 10(11):2730. https://doi.org/10.3390/foods10112730

Rumgay H, Murphy N, Ferrari P, Soerjomataram I (2021) Alcohol and Cancer: Epidemiology and Biological Mechanisms. Nutrients 13(9):3173. https://doi.org/10.3390/nu13093173

Sadowski A, Houck RC (2024) Alcoholic Neuropathy. In: StatPearls. StatPearls Publishing, Treasure Island (FL)

Saunder CJ, Silver WL (2016) Anatomy and physiology of chemesthesis. In: David Boillet, Hayes JE, McDonald ST, Prescott J (eds) Chemesthesis: Chemical touch in food and eating. John Wiley & Sons, Ltd., pp 77–91

Sawynok J (2005) Topical Analgesics in Neuropathic Pain. CPD 11(23):2995–3004. https://doi.org/10.2174/1381612054865019

Scoville WL (1912) Note on capsicums. The Journal of the American Pharmaceutical Association 5:453–454

Shaffer SW, Harrison AL (2007) Aging of the Somatosensory System: A Translational Perspective. Physical Therapy 87(2):193–207. https://doi.org/10.2522/ptj.20060083

Silvaroli JA, Pleshinger MJ, Banerjee S, Kiser PD, Golczak M (2017) Enzyme That Makes You Cry–Crystal Structure of Lachrymatory Factor Synthase from *Allium cepa*. ACS Chem Biol 12(9):2296–2304. https://doi.org/10.1021/acschembio.7b00336

Simone DA, Nolano M, Johnson T, Wendelschafer-Crabb G, Kennedy WR (1998) Intradermal Injection of Capsaicin in Humans Produces Degeneration and Subsequent Reinnervation of Epidermal Nerve Fibers: Correlation with Sensory Function. J Neurosci 18(21):8947–8959. https://doi.org/10.1523/JNEUROSCI.18-21-08947.1998

Simons CT (2016) Types of chemesthesis III. Tingling and numbing. In: McDonald ST, Bolliet DA, Hayes JE (eds) Chemesthesis, 1st edn. Wiley, pp 134–153

Simons CT, Carstens E (2008) Oral Chemesthesis and Taste. In: The Senses: A Comprehensive Reference. Elsevier, pp 345–369

Slack JP (2016) Molecular Pharmacology of Chemesthesis. In: Chemosensory Transduction. Elsevier, pp 375–391

Spinelli S, De Toffoli A, Dinnella C, Laureati M, Pagliarini E, Bendini A, Braghieri A, Gallina Toschi T, Sinesio F, Torri L, Gasperi F, Endrizzi I, Magli M, Borgogno M, Di Salvo R, Favotto S, Prescott J, Monteleone E (2018) Personality traits and gender influence liking and choice of food pungency. Food Quality and Preference 66:113–126. https://doi.org/10.1016/j.foodqual.2018.01.014

Spinelli S, Monteleone E (2021) Food Preferences and Obesity. Endocrinol Metab 36(2):209–219. https://doi.org/10.3803/EnM.2021.105

Staudinger JL (2019) Clinical applications of small molecule inhibitors of Pregnane X receptor. Molecular and Cellular Endocrinology 485:61–71. https://doi.org/10.1016/j.mce.2019.02.002

Stevens DA, Lawless HT (1986) Putting out the fire: Effects of tastants on oral chemical irritation. Perception & Psychophysics 39(5):346–350. https://doi.org/10.3758/BF03203002

Su T, Gao X, Li H, Zhang L, Han P, Chen H (2022) Frequent spicy food consumption is associated with reduced capsaicin and salty taste sensitivity but unchanged sour taste or intranasal trigeminal sensitivity. Food Quality and Preference 96:104411. https://doi.org/10.1016/j.foodqual.2021.104411

Takahashi S, Kurogi M, Saitoh O (2021) The diversity in sensitivity of TRPA1 and TRPV1 of various animals to polyphenols. Biomed Res 42(2):43–51. https://doi.org/10.2220/biomedres.42.43

Takaishi M, Uchida K, Suzuki Y, Matsui H, Shimada T, Fujita F, Tominaga M (2016) Reciprocal effects of capsaicin and menthol on thermosensation through regulated activities of TRPV1 and TRPM8. J Physiol Sci 66(2):143–155. https://doi.org/10.1007/s12576-015-0427-y

Tewksbury JJ, Reagan KM, Machnicki NJ, Carlo TA, Haak DC, Peñaloza ALC, Levey DJ (2008) Evolutionary ecology of pungency in wild chilies. Proc Natl Acad Sci USA 105(33):11808–11811. https://doi.org/10.1073/pnas.0802691105

The Nobel Assembly at Karolinska Institutet (2021) The 2021 Nobel Prize in Physiology or Medicine. In: The 2021 Nobel Prize in Physiology or Medicine. https://www.nobelprize.org/prizes/medicine/2021/summary/

Thibodeau M, Bajec M, Pickering G (2017) Orosensory responsiveness and alcohol behaviour. Physiology & Behavior 177:91–98. https://doi.org/10.1016/j.physbeh.2017.04.019

Thiele R, Mueller-Seitz E, Petz M (2008) Chili Pepper Fruits: Presumed Precursors of Fatty Acids Characteristic for Capsaicinoids. J Agric Food Chem 56(11):4219–4224. https://doi.org/10.1021/jf073420h

Törnwall O (2013) Genetic and environmental influences on chemosensory perception and preferences - Academic Dissertation. University of Helsinki, Helsinki, Finland

Tuccillo F, Lampi A-M, Katina K, Sandell M (2024) Exploring the lack of liking for faba bean ingredients with different sensory profiles. Food Quality and Preference 118:105198. https://doi.org/10.1016/j.foodqual.2024.105198

Viana F (2011) Chemosensory Properties of the Trigeminal System. ACS Chem Neurosci 2(1):38–50. https://doi.org/10.1021/cn100102c

Wang Y, Zhong K, Shi B, Wang H, Liu L, Zhang L, Zhao L, Gao H (2022) Cross-modal effect of capsaicin and pepper oleoresin on the enhancement of saltiness perception in a NaCl model solution. Food Quality and Preference 98:104542. https://doi.org/10.1016/j.foodqual.2022.104542

Ward C (2016) Some like it hot! Sensory analysis of products containing chemesthetic compounds. In: McDonald ST, Bolliet DA, Hayes JE (eds) Chemesthesis, 1st edn. Wiley, pp 166–184

Weir EM, Exten C, Gerkin RC, Munger SD, Hayes JE (2023) Transient loss and recovery of oral chemesthesis, taste and smell with COVID-19: a small case-control series. Infectious Diseases (except HIV/AIDS)

Welch CJ, Regalado EL, Welch EC, Eckert IMK, Kraml C (2014) Evaluation of capsaicin in chili peppers and hot sauces by MISER HPLC-ESIMS. Anal Methods 6(3):857–862. https://doi.org/10.1039/C3AY41953C

Wierenga MR, Crawford CR, Running CA (2020) Older US adults like sweetened colas, but not other chemesthetic beverages. Journal of Texture Studies 51(5):722–732. https://doi.org/10.1111/jtxs.12549

World Health Organization (2023) Healthy diet. https://www.who.int/health-topics/healthy-diet#tab=tab_1

Zhang M, Ma Y, Ye X, Zhang N, Pan L, Wang B (2023a) TRP (transient receptor potential) ion channel family: structures, biological functions and therapeutic interventions for diseases. Sig Transduct Target Ther 8(1):261. https://doi.org/10.1038/s41392-023-01464-x

Zhang W, Zhang Q, Wang L, Zhou Q, Wang P, Qing Y, Sun C (2023b) The effects of capsaicin intake on weight loss among overweight and obese subjects: a systematic review and meta-analysis of randomised controlled trials. Br J Nutr 130(9):1645–1656. https://doi.org/10.1017/S0007114523000697

Zhu Y, Li X, Jiang S, Zhang Y, Zhang L, Liu Y (2023a) Multi-dimensional pungency and sensory profiles of powder and oil of seven chili peppers based on descriptive analysis and Scoville heat units. Food Chemistry 411:135488. https://doi.org/10.1016/j.foodchem.2023.135488

Zhu Y, Thaploo D, Han P, Hummel T (2023b) Processing of Sweet, Astringent and Pungent Oral Stimuli in the Human Brain. Neuroscience 520:144–155. https://doi.org/10.1016/j.neuroscience.2023.03.011

APPENDIX 1.

Role of genetic variation
in bitter taste receptors associated with chemesthetic perception

Sulo Roukka, Laila Seppä, and Mari Sandell

Sulo Roukka
Department of Food and Nutrition
University of Helsinki, Finland
sulo.roukka@helsinki.fi
@suloroukka

Laila Seppä
Department of Food and Nutrition
University of Helsinki, Finland

Mari Sandell
Department of Food and Nutrition
University of Helsinki, Finland
Functional Foods Forum
University of Turku, Finland

INTRODUCTION

Bitter taste sensitivity is known to be influenced by various bitter taste receptor genes (BTRGs) which can explain individual differences. To understand better the role of genetic variation in bitter taste receptors, we investigated, whether BTRGs in **Figure 1** have associations with chemesthetic sensitivity.

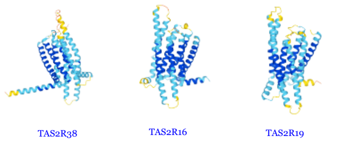


Figure 1. Bitter taste receptor genes e.g., *h*TAS2R38, *h*TAS2R16, and *h*TAS2R19 were studied in this research.

Links for the gene pictures:
https://www.genecards.org/cgi-bin/carddisp.pl?gene=TAS2R38
https://www.genecards.org/cgi-bin/carddisp.pl?gene=TAS2R16&keywords=hTAS2R16
https://www.genecards.org/cgi-bin/carddisp.pl?gene=TAS2R19&keywords=TAS2R19

In FoodTaste Finland research program (*Human taste sensitivity and multisensory perception of food*), oral chemesthetic sensitivity was measured using liquid samples of different chemesthetic compounds in **Table 1** (Roukka et al. 2021; 2023).

Then, the association between chemesthetic sensitivity and BTRGs was studied with Partial Least Square Regression (PLS) analysis. The PLS models are presented in **Figure 2** and analysis in **Table 2.**

Table 1. Prototypic compounds used in the study samples (Roukka et al. 2021; 2023).

Chemesthetic quality	Prototypic compound
Pungent	Capsaicin (CAS: 404-86-4) $C_{18}H_{27}NO_3$
Astringent	Aluminum ammonium sulfate (CAS: 7784-26-1) $AlNH_4(SO_4)^2 \cdot 12H_2O$
Cooling	*l*-Menthol (CAS: 2216-51-5) $C_{10}H_{20}O$

MATERIAL AND METHODS

FoodTaste Finland (*N*=205)

Functional Foods Forum Sensory Lab (University of Turku, Finland)

Chemesthetic sensitivity (Roukka et al. 2021;2023)

Partial Least Square Regression (Unscrambler X 10.5.1 by CAMO Software)

RESULTS

Table 2. BTRGs and chemesthetic quality-specific sensitivity formed clusters (Figure 2).

Bitter taste receptor genes	PLS models (two first factors) with chemesthetic sensitivity groups and BTRGs-genotypes
*h*TAS2R19 R299C (rs10772429)	**Figure 2 A**: 29% of the variation in BTRG explained 3% of the variation in the sensitivity for **astringency.** Participants with genotype **R/C** are clustered closer to hyposensitive and **R/R** closer to semisensitive groups.
*h*TAS2R16 (rs1308724)	**Figure 2 B**: 33% of the variation in BTRG explained 3% of the variation in the sensitivity for **pungency.** Participants with genotype: **C/C** are closer to hypersensitive, **C/G** closer to semisensitive, and **G/G** closer to hyposensitive groups.
*h*TAS2R38	**Figure 2 C:** 33% of the variation in BTRG explained 7% of the variation in the sensitivity for **cooling.** Participants with genotype **PAV/AVI** are closer to hypo- and hypersensitive groups.
*h*TAS2R16 (rs846672)	**Figure 2 D:** 33% of the variation in BTRG explained 7% of the variation in the sensitivity for **cooling.** Participants with genotypes **C/A** are closer to hypersensitive, and **C/C** closer to semisensitive group.

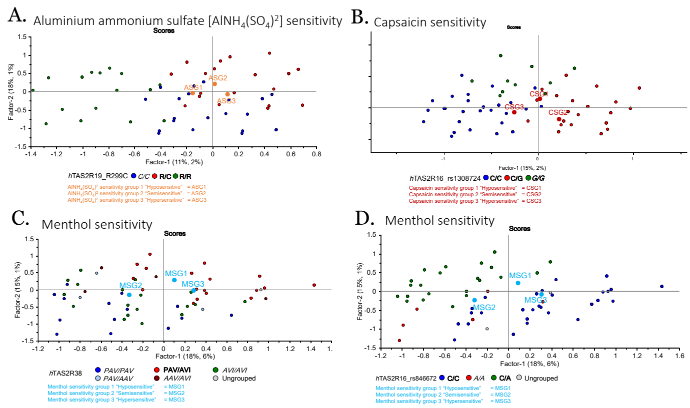


Figure 2. The PLS-score plots of sensitivity for astringency (A), pungency (B), and cooling (C and D) with genotypes of bitter taste receptor genes (*h*TAS2R19, *h*TAS2R16, and *h*TAS2R38) being X-variables. Different genotypes were used as category variables labelling genetic background of study participants (A: *h*TAS2R19, B: *h*TAS2R16, C: *h*TAS2R38, D: *h*TAS2R16).

TAKE HOME MESSAGES

1. **Genetic variation in bitter taste receptor genes had some interactions with quality-specific chemesthetic sensitivity**
2. **PLS-regression analyses showed clusters among study participants when BTRGs-genotypes were used as background factors**
3. **For further research, other bitter taste receptor genes and their genotypes might show clustering effects in quality-specific chemesthetic sensitivity**

References

Roukka S, Puputti S, Aisala H, Hoppu U, Seppä L, Sandell MA. The Individual Differences in the Perception of Oral Chemesthesis Are Linked to Taste Sensitivity. Foods 2021; 10(11):2730. doi:10.3390/foods10112730

Roukka S, Puputti S, Aisala H, Hoppu U, Seppä L, Sandell M. Factors explaining individual differences in the oral perception of capsaicin, l- menthol, and aluminum ammonium sulfate. Clin Transl Sci. 2023;00:1-13. doi:10.1111/cts.13587

Acknowledgments

Dr. Sari Puputti, Dr. Heikki Aisala, and Dr. Ulla Hoppu for collecting and processing the sensory data.
Dr Paul A.S. Breslin and the Breslin lab for mentoring in BTRGs analyses.
Hilkka Terho and Annamari Kumpulainen for genotyping.
Academy of Finland, University of Helsinki, University of Turku for funding.
We also want to thank all the participants who attended to this research.

Conflicts of Interest

The authors declare no conflict of interest.

HELSINGIN YLIOPISTO
HELSINGFORS UNIVERSITET
UNIVERSITY OF HELSINKI
MAATALOUS-METSÄTIETEELLINEN TIEDEKUNTA
AGRIKULTUR-FORSTVETENSKAPLIGA FAKULTETEN
FACULTY OF AGRICULTURE AND FORESTRY

APPENDIX 2.

Sensometrics
ECR3.5
Doctoral Researcher, M.Sc. Sulo Roukka
Department of Food Science and Nutrition
University of Helsinki
Senses and Food Research Team
@SuloRoukka
sulo.roukka@helsinki.fi

Factors explaining individual differences in sensitivity to oral pungency elicited by capsaicin among Finnish adults

Sulo Roukka, Sari Puputti, Heikki Aisala, Ulla Hoppu, Laila Seppä, and Mari Sandell*

CAPSAICIN AND THE PUNGENCY PERCEPTION

Capsaicin (Figure 1) can chemically stimulate the perception of pungency by directly activating the human somatosensory system.
h-TRPV1 (transient receptor potential cation channel, subfamily V, member 1) is selectively activated by capsaicin which conveys the perception of pungency via the *Trigeminal Nerve (Cranial Nerve V)* (Caterina et al. 1997).
Our previous study has shown that people can be classified into different sensitivity groups (hyposensitive 28.1%, semi-sensitive 29.6%, and hypersensitive 42.2%) based on their intensity ratings to oral pungency measured on five different capsaicin concentration levels (Roukka et al. 2021).
Our aim is to investigate the potential factors (Table 1) explaining individual differences in capsaicin elicited pungency perception.

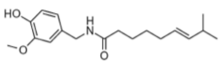


Figure 1. Capsaicin ($C_{18}H_{27}NO_3$) is a compound that can be isolated from chili peppers

MATERIAL AND METHODS

Laboratory: Functional Foods Forum, the sensory laboratory (ISO-8589) at the University of Turku
Questionnaire: Compusense five Plus 5.6 software (Compusense, Guelph, ON, Canada). Intensity line scales (0 "no sensation" to 10 "very strong") and recognition section
Pungency samples: Capsaicin solutions (zero; 0.049; 0.088; 0.154; 0.275; and 0.491 µM) in Figure 2
Participants: Finnish-speaking adults N_{total} = 199
Pungency sensitivity: Roukka et al. 2021
Pungency recognition score: The average number of all correctly identified capsaicin samples
Data Analyses: Chi-squared test for association and Multinomial logistic regression for relationship (ns= nonsignificant, * p<0.05, and ** p<0.01)
Statistical Softwares: IBM SPSS Statistic 27.0 (IBM Corporation, Armonk, NY, USA) and Microsoft Excel (Microsoft Office 2016)

Figure 2. Capsaicin solutions were coded and served in randomized order for the participants

FOODTASTE FINLAND

FoodTaste Finland program includes sensory studies of smell, taste, chemesthesis, and multisensory perception
Focus on individual differences in sensory perception
Funded by the Academy of Finland (MS252005, 256176, 263747, 309408), the University of Turku, and the University of Helsinki

Table 1. Background factors (n %), N_{total} = 199

Intrinsic factors		Extrinsic factors	
Gender	Males (19.6%)	Smoking status	Non-smokers (73.4%)
	Females (79.4%)		Current/ Former smokers (25.1%)
Age	19–34 y. (42.2%)	BMI	<25.0 (54.8%)
	35–49 y. (24.6%)		25.0–29.9 (25.1%)
	50–79 y. (28.6%)		≥30.0 (18.1%)

RESULTS

Recognition of the oral pungency in Figure 3

Chi-squared test and Pungency sensitivity
- **Gender**: χ^2 [2] = **7.76***, Females are more likely to be hypersensitive and males hyposensitive
- **Age:** χ^2 [4] = 3.67, ns
- **BMI:** χ^2 [4] = 3.02, ns
- **Smoking status:** χ^2 [2] = 4.52, ns

Multinomial logistic regression and Pungency sensitivity
- **Model fit statistics:** -2 Log-likelihood: 253.42; χ^2 (14) = 28.71, $p \leq 0.05$; Nagelkerke Pseude R-square: 0.154; and Goodness of fit: ns
- **Gender:** Males were **3.07*** times more likely to belong in the hyposensitive than the hypersensitive group (Ref: Females)
- **Age:** Older participants (50–79 y.) were **2.65*** times more likely to be in the hyposensitive than the semi-sensitive group (Ref: younger participants aged 19–34 y.)
- **BMI:** Nonsignificant results
- **Smoking status:** Nonsignificant results
- **Pungency recognition score:** Participants with higher recognition scores were **12.5**** times more likely to belong in the hypersensitive group than in the hyposensitive group. Also, those with higher recognition scores were **11.1**** times more likely to belong in the hypersensitive group than in the semi-sensitive group

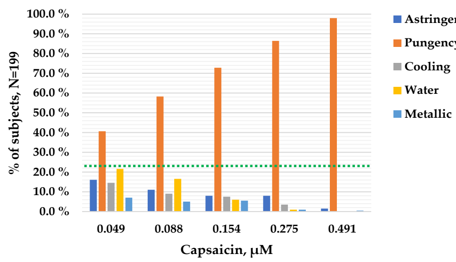


Figure 3. Results for pungency recognition. Capsaicin samples were used for measuring the intensity of pungency perception (Roukka et al. 2021) and recognition. Participants had to select the modality that they perceived from samples. The green dotted line indicate the participant level of those who correctly identified all the samples as pungency (23.1%)

"Please feel free to read our latest publication (Roukka et al. 2021) and learn more about the individual differences in the perception of oral chemesthesis!"

TAKE HOME MESSAGES

Females seem to be more sensitive to capsaicin elicited pungency than males
BMI groups and smoking status did not show associations or predict the pungency sensitivity
The older participants would be more likely in the hyposensitive than the semisensitive group when referring to younger participants
Higher pungency recognition score indicates higher sensitivity to pungency perception

REFERENCES

Caterina, M. J., Schumacher, M. A., Tominaga, M., Rosen, T. A., Levine, J. D., & Julius, D. (1997). The capsaicin receptor: a heat-activated ion channel in the pain pathway. *Nature*, 389(6653), 816–824. https://doi.org/10.1038/39807

Roukka, S., Puputti, S., Aisala, H., Hoppu, U., Seppä, L., & Sandell, MA. (2021). The individual differences in the perception of oral chemesthesis are linked to taste sensitivity. *Foods*, 10(11), 2730. https://doi.org/10.3390/foods10112730

SPECIAL THANKS FOR ALL THE PROJECT MEMBERS AND TO ALL THE PARTICIPANTS WHO ATTENDED TO OUR RESEARCH!

Tenth European Conference on Sensory and Consumer Research
EuroSense2022
A Sense of Earth
13–16 September 2022 | Turku, Finland

HELSINGIN YLIOPISTO
HELSINGFORS UNIVERSITET
UNIVERSITY OF HELSINKI
MAATALOUS-METSÄTIETEELLINEN TIEDEKUNTA
AGRIKULTUR-FORSTVETENSKAPLIGA FAKULTETEN
FACULTY OF AGRICULTURE AND FORESTRY