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Enhancing Sensory Characteristics of Chocolate Confectionery:
A Technological Approach to Optimise Taste, Texture and Aroma Perception

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"There is no real ending. It's just the place where you stop the story." — Frank Herbert

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Contents

Notation

Latin Letters

Symbol	Unit	Meaning
d	m	diameter
F	N	force
N	m s^{-1}	sliding velocity
T	K	temperature
W	N m^{-2}	load

Greek Letters

Symbol	Unit	Meaning
η	$Pa\,s$	dynamic viscosity
μ	-	friction factor

Subscripts

Symbol	Meaning
H	hazelnut oil
N	normal
R	frictional
S	sugar

Abbreviations

Abbrevation	Meaning
BMI	body mass index
BTP	ball-on-three-plates
DEMF	dynamically enhanced membrane foaming
DSC	differential scanning calorimetry
EEG	electroencephalography
ERP	event-related potential
HSD	honestly significant difference
LME	linear mixed-effects model
PBS	phosphate-buffered saline
PDMS	polydimethylsiloxane
SLA	stereolithography
SSHE	scraped surface heat exchanger
2AFC	two-alternative forced choice

Summary

This thesis explores sensory perception, with a particular focus on understanding the nuances of sweetness. It begins with an in-depth exploration of how textural properties of chocolate, like viscosity and melting behavior, influence its sensory attributes. Employing tribological studies and incorporating artificial saliva, a new custom geometry and other biomimetic improvements, the research reveals the significant role of texture in shaping taste experiences.

Expanding the scope, the study then examines the impact of surface structuring on sweetness and aroma perception. Findings from these investigations highlight how textural modifications, such as air incorporation and surface patterns, can enhance sensory experiences, particularly in chocolate products. This chapter underscores the potential of using placement as a tool for manipulating taste perception.

The thesis takes a neuroscientific turn, linking sensory evaluations to physiological and neurological responses, including pupil dilation and event-related potentials (ERPs). This approach offers insights into how different sugar concentrations and textures are processed by the body and brain, highlighting the distinct ways in which sensory stimuli are perceived.

The research delves into the cognitive aspects of sensory testing, assessing how the anticipation of a rating task affects physiological responses. This investigation indicates that the cognitive load of anticipating a rating can influence physiological markers of sensory experiences.

In conclusion, this thesis provides a multifaceted view of sensory perception, emphasizing the complexity and diversity of factors influencing how sweetness is perceived. The findings offer valuable insights for future research in sensory science and practical applications in food product development and consumer research. By exploring the intricate relationships between physical properties of food, personal characteristics, and sensory experiences, the study contributes significantly to the broader understanding of taste perception and sensory evaluation methodologies.

Zusammenfassung

In dieser Arbeit wird die sensorischen Wahrnehmung untersucht, mit einem besonderen Schwerpunkt auf dem Verständnis der Nuancen von Süße. Sie beginnt mit einer ausführlichen Untersuchung darüber, wie die texturalen Eigenschaften von Schokolade, wie Viskosität und Schmelzverhalten, ihre sensorischen Attribute beeinflussen. Durch den Einsatz tribologischer Studien und die Einbeziehung von künstlichem Speichel, einer neuen benutzerdefinierten Geometrie und anderen biomimetischen Verbesserungen, offenbart die Forschung die bedeutende Rolle der Textur bei der Gestaltung von Geschmackserlebnissen.

Die Studie erweitert den Rahmen und untersucht die Auswirkungen von Oberflächenstrukturen auf Süße und Aromawahrnehmung. Die Ergebnisse dieser Untersuchungen heben hervor, wie texturale Modifikationen, wie Lufteinschlüsse und Oberflächenmuster, sensorische Erlebnisse verstärken können, insbesondere bei Schokoladenprodukten. Dieses Kapitel unterstreicht das Potenzial der Verwendung von Platzierung als Werkzeug zur Manipulation der Geschmackswahrnehmung.

Die Arbeit nimmt eine neurowissenschaftliche Wendung und verknüpft sensorische Bewertungen mit physiologischen und neurologischen Reaktionen, einschließlich Pupillenerweiterung und ereignisbezogenen Potenzialen (ERPs). Dieser Ansatz bietet Einblicke darin, wie unterschiedliche Zuckerkonzentrationen und Texturen vom Körper und Gehirn verarbeitet werden und hebt die unterschiedlichen Arten hervor, in denen sensorische Reize wahrgenommen werden.

Die Forschung vertieft sich in die kognitiven Aspekte der sensorischen Testung und bewertet, wie die Erwartung einer Bewertungsaufgabe die physiologischen Reaktionen beeinflusst. Diese Untersuchung deutet darauf hin, dass die kognitive Belastung durch die Erwartung einer Bewertung die physiologischen Marker von sensorischen Erlebnissen beeinflussen kann.

Zusammenfassend bietet diese Arbeit einen facettenreichen Blick auf die sensorische Wahrnehmung und betont die Komplexität und Vielfalt der Faktoren, die beeinflussen, wie Süße wahrgenommen wird. Die Erkenntnisse bieten wertvolle Einsichten für zukünftige Forschungen in der sensorischen Wissenschaft sowie praktische Anwendungen in der Produktentwicklung von Lebensmitteln und der Verbraucherforschung. Indem sie die komplexen Beziehungen zwischen den physikalischen Eigenschaften von Lebensmitteln, persönlichen Merkmalen und sensorischen Erlebnissen erforscht, leistet die Studie einen bedeutenden Beitrag zum breiteren Verständnis der Geschmackswahrnehmung und der Methoden der sensorischen Bewertung.

1 Introduction

In recent decades, the prevalence of obesity worldwide has seen a dramatic increase, posing a significant public health challenge. This rise in obesity rates is attributed mainly to two factors: the increased consumption of highly processed, energy-dense convenience foods, and a more sedentary lifestyle characterized by decreasing levels of physical activity. This combination leads to an imbalance between energy intake and expenditure, subsequently resulting in overweight and obesity, which carry serious health risks. One of the primary strategies to address this growing concern is reducing the consumption of high-calorie nutrients, particularly sugar and fat. These are the major contributors to the overall energy content of the diet.

However, reformulating food products to contain less sugar and fat presents a significant challenge. Sugar and fat play crucial roles not only in taste but also in texture perception, two key factors driving consumer acceptance of food products. The reduction of these components often leads to products that are less appealing to consumers. Thus, food scientists and manufacturers face the task of altering food formulations without compromising the sensory attributes of the products.

Chocolate serves as a pertinent example of this challenge. As a sweet food in high demand, chocolate typically contains large amounts of sugar and fat. One of the defining aspects of high-quality chocolate is its smoothness, a key factor in consumer acceptance. Sugar and fat contribute significantly to chocolate's texture by influencing its melting characteristics and particle size. Reducing the content of sugar and fat in chocolate, therefore, poses a risk to its perceived quality and consumer appeal.

The challenge lies in achieving a balance between nutritional improvements and maintaining the sensory qualities that drive consumer preferences. The case of chocolate exemplifies the broader challenge faced by the food industry in creating healthier products without sacrificing taste and texture. Advancements in food science and technology are crucial in overcoming these challenges, paving the way for the development of healthier food options that still satisfy consumer expectations.

2 Background

2.1 Physiology of sweet taste perception

Sweet taste perception is a fascinating and complex sensory process, primarily occurring in the oral cavity, notably on the tongue. This sense plays a crucial role in dietary choices, influencing nutrition and overall health. The perception of sweetness is not just a simple gustatory experience but involves intricate molecular interactions and signaling pathways within taste cells.

Anatomical and molecular Basis

The human taste system, particularly the taste buds, is foundational in sweet taste perception. These taste buds are influenced by a combination of hormonal modulation, genetic chemosensory variation, macronutrient selection, and eating behavior (Loper *et al.*, 2015). Each taste bud comprises numerous taste receptor cells, which are responsible for detecting sweet substances.

Central to the detection of sweet taste are two specific taste receptors: taste receptor 1 member 2 and taste receptor 1 member 3. These receptors, belonging to the G protein-coupled receptor family, are crucial for sweet taste detection and ligand selectivity. Their discovery and characterization have significantly advanced our understanding of how sweetness is perceived at a molecular level. These receptors, when activated by sweet substances, initiate a cascade of intracellular signaling processes leading to the perception of sweetness (Sclafani, 2007). The interaction of sweet substances, such as sucrose, with these TRs sets off a cascade of cellular events. The binding of sucrose to the T1R2/T1R3 receptor complex triggers a sweetness response through membrane depolarization. This depolarization is a critical step leading to the release of ATP and the activation of afferent neurons, thereby transmitting the perception of sweetness to the brain. The detailed mechanism of this process involves several G proteins, including α-gustducin, Gβ3, and Gγ13. Their dissociation following sucrose binding leads to increased phospholipase C-2 activity. This enzymatic action causes the release of calcium via the inositol 1,4,5-triphosphate receptor, type 3. The subsequent opening of the transient receptor potential ion channel TRPM5 results in further depolarization of the membrane, a pivotal step for the release of ATP and the initiation of sweetness perception.

Apart from sucrose, a diverse range of non-carbohydrate molecules, proteins, and artificial sweeteners can also interact with T1R2 and T1R3 receptors, eliciting a sweet perception. This diversity indicates the broad selectivity and adaptability of these receptors in recognizing various sweet tastants.

Interestingly, all sweet perceived tastants share common threshold values, critical for understanding sweetness perception. The detection threshold refers to the minimum concentration of a tastant in an aqueous solution that can be distinguished from distilled water, while the recognition threshold is the lowest concentration eliciting identifiable taste characteristics. The increase in sweetness perception with rising tastant concentration continues until the terminal threshold is reached, beyond which further increases in concentration do not enhance the sweetness perception

Sweet taste in health and disease

The perception of sweet taste also has implications for health and disease. For instance, alterations in sweet taste perception have been observed in conditions like diabetes, where patients often experience a heightened perception of sweetness. This altered perception can influence dietary choices and glucose control, thus impacting the management of the disease. Furthermore, research has shown that sweet taste receptors are not only located in the oral cavity but also in other parts of the body, such as the gastrointestinal tract, where they play roles in glucose absorption and insulin secretion (Fernstrom *et al.*, 2012)

Influence of external factors

External factors such as diet, smoking, and certain medications can influence sweet taste perception. For example, smoking has been shown to increase the threshold for sweet taste, potentially altering taste preferences and food choices (Akal *et al.*, 2003). Dietary habits can also have a long-term impact on taste receptor sensitivity and function.

Technological and research advancements

Advancements in research methodologies and technologies have significantly contributed to our understanding of sweet taste physiology. Techniques like genetic engineering, molecular biology, and neuroimaging have provided deeper insights into the mechanisms underlying sweet taste perception. These advancements have paved the way for potential therapeutic interventions targeting taste perception, which could have implications for managing conditions like obesity and diabetes.

In summary, the physiology of sweet taste perception is a dynamic and multifaceted process, influenced by anatomical, molecular, genetic, hormonal, and environmental factors. This complex interplay not only determines our perception and enjoyment of sweet flavors but also has significant implications for nutrition, health, and disease management. Understanding these mechanisms is crucial for developing strategies to promote healthy eating behaviors and treat taste-related disorders.

2.2 Physiology of texture perception

The texture of food, encompassing attributes like thickness, hardness, stickiness, and smoothness, plays a crucial role in the overall sensory experience. In the context of sugar reduction in food products, these texture attributes are expected to undergo significant changes due to alterations in the food matrix. This chapter focuses on understanding these textural modifications, particularly the perception of smoothness, which is intricately linked to the frictional forces experienced during consumption.

Oral Sensory Mechanisms

The perception of texture, particularly in foods, begins in the oral cavity. Factors like oral sensitivity, tongue movements, saliva composition, and temperature play significant roles in determining how we perceive the texture of semisolids (Engelen and Van Der Bilt, 2008). The mechanical and acoustical properties of food are sensed by receptors in the tongue and jaws. This sensory information is processed to form a perception of texture, which is critical for food enjoyment and acceptance (Peleg, 1993). The concept of smoothness in food texture lacks a uniform definition in the literature, highlighting the complexity of this sensory attribute. Different definitions offer varying perspectives: some describe smoothness in terms of the sensation detected when the tongue glides a sample across the roof of the mouth, emphasizing the tactile interaction between the food and oral surfaces. Others view smoothness as a surface property proportional to the frictional force experienced during consumption. Engelen and Van Der Bilt (2008) provide a more detailed definition, associating smoothness with the inverse of the friction force required for skin or food to slip across each other. Despite the varied definitions, a common thread in most descriptions of smoothness is its relationship with frictional force, a concept first elucidated by Kokini *et al.* (1977).

$$\text{"}smoothness\text{"} \propto \frac{1}{\mu \cdot W} \tag{2.1}$$

Where W is the applied load by the tongue and μ is the friction factor between the rubbed surfaces, lubricated by the food. This connection is fundamental to understanding how smoothness is perceived during the consumption of food products. The frictional force, a characteristic not directly measurable by rheological methods, is pivotal in determining the tactile sensation of smoothness.

Integration with Other Senses

Texture perception is not just limited to mechanical sensing; it is a multisensory process involving vision, hearing, somesthesis (bodily sensations), and kinesthesis (movement sensation). Oral processes such as motility, saliva production, and temperature also affect how texture is perceived (Wilkinson *et al.*, 2000). For example, the texture of cheese is perceived differently throughout the consumption process, influenced by dynamic factors like swallowing time, which affects the physical properties of cheese boluses in the mouth (Saint-Eve *et al.*, 2015).

Physiological basis and brain Processing

The primary somatosensory cortex in the brain is critical for texture discrimination, with both its deep and superficial layers playing a crucial role in this sensory process (Park *et al.*, 2020). Tactile stimuli are decoded by the somatosensory system through activation of low-threshold mechanoreceptors in the spinal cord, which then convey information to the brain for processing (Abraira and Ginty, 2013).

Challenges in understanding texture perception

Despite advancements in understanding texture perception, there are still challenges, particularly in relating physical measurements to sensory experiences. Oral tribological processes (the study of friction, lubrication, and wear in the mouth) provide valuable insights into texture-related sensory perceptions, but quantifying these relationships remains complex (Pradal and Stokes, 2016a). Additionally, understanding consumer preferences in terms of texture and mouthfeel is a challenging task for product developers and manufacturers, due to the limited physiological understanding of these sensations (Guinard and Mazzucchelli, 1996). Rheology, which deals with the flow and deformation of matter, has traditionally been used to study food texture. However, it has become increasingly clear that rheology alone cannot fully explain the relationship between food structure and texture perception. This limitation arises because rheology does not account for the tactile sensations experienced in the oral cavity, particularly those related to frictional forces.

In conclusion, the physiology of texture perception is a complex interplay of mechanical, acoustical, and multisensory processes. It involves various oral and cerebral mechanisms, each contributing to the overall experience of texture. Understanding these processes not only enhances our knowledge of sensory perception but also has practical applications in food science, product development, and consumer research. To accurately measure and understand the perception of smoothness, it is essential to delve into the oral tactile sensations. This involves exploring how the physical interaction between food and oral surfaces, mediated by frictional forces, contributes to the overall texture perception. By focusing on these tactile interactions, researchers can gain a deeper insight into how sugar reduction and other alterations in food composition affect the sensory experience of food texture.

2.3 Cross-modal interactions in food perception

Cross-modal interactions between aroma, taste, and texture significantly influence the perception of food. These interactions are complex, making it difficult to distinctly analyze each component's contribution to the overall sensory experience (Keser and Ozcan, 2020). The interactions between aroma, taste, and texture are critical in shaping food flavor perception. For example, the texture of a food can alter the release and perception of its aroma and taste, thereby influencing the overall flavor experience (Thomas-Danguin *et al.*, 2016).

The texture of food can influence how odor-induced changes in taste perception are experienced. Softer textures in food tend to benefit more from odor-induced enhancements in taste perception (Thomas-Danguin *et al.*, 2015). Interestingly, the texture of packaging can also affect the perceived taste of the product inside. If there is sensory incongruence between the packaging texture and the product texture, it can negatively affect product taste and consumer satisfaction (Ferreira, 2019).

The addition of aroma to foods can make the perception of certain textures, such as hardness and juiciness, less dominant. This demonstrates that aroma can influence texture-aroma and taste-aroma interactions in food perception (Charles *et al.*, 2017).

In conclusion, the interactions between taste and texture in food perception are integral to our sensory experience. They not only determine how we perceive individual flavors and textures but also how these perceptions combine to create a holistic sensory experience. Understanding these interactions is crucial for food product development, culinary arts, and nutrition, as they influence consumer preferences and eating behaviors.

2.4 Oral tribological processes

Soft tribology in the context of food texture perception is an emerging field that focuses on understanding the frictional properties of foods and their impact on sensory perception and oral processing. This field provides significant insights into how different textures are perceived in the mouth, contributing to the overall sensory experience of food consumption. Tribological measurements involve the rubbing of a material between two surfaces, and measuring the frictional forces occurring in the contact zone. This can be used to evaluate the lubrication properties of materials, for example liquid or semi-solid foods. The friction factor (µ) is plotted as a function of the sliding velocity to create a Stribeck curve. Friction factor is calculated the following way:

$$\mu = \frac{F_R}{F_N} \tag{2.2}$$

where F_R is the friction force and F_N is the tribological normal force.
Often times the Hersey number:

$$\text{Hersey number} = \frac{\eta \cdot N}{W} \tag{2.3}$$

where η is the dynamic viscosity of the lubricant, N is the sliding velocity and W is the load, is used to create normalised Stribeck curves. Stribeck curves are generally accepted as the output of friction analysis, and are used to interpret the lubrication properties of the involved materials (Pradal and Stokes, 2016b).

Role of soft tribology in food texture perception

Soft tribology mimics the manipulations of food in the mouth by examining the lubricated interactions of surfaces, which are vital for the oral perception of food texture and mouthfeel. This approach helps to understand how different food textures behave during consumption (Upadhyay and Chen, 2020). Lubrication properties of food, measured through soft tribology, play a dominating role in the perception of food texture and mouthfeel, significantly contributing to the sensory experience (Prakash *et al.*, 2013).

Synchronization with oral processing dynamics

Soft tribology is crucial in synchronizing the measurement of food texture with the dynamics of oral processing. This synchronization allows for a more comprehensive understanding of how food textures are perceived during the actual process of eating (Ahmed *et al.*, 2017). For instance, the assessment of dairy products' sensory mouthfeel in relation to fat content can be quickly determined through tribological methods, providing insights into their texture perception (Nguyen *et al.*, 2016).

In the context of semi-fluid foods, soft tribology involves the preferential entrainment of different phases and components at a narrow gap. This process affects the perception of surface-related mouthfeel attributes, thus differentiating foods with similar rheological properties (Selway and Stokes, 2013b).

Predicting oral behavior and assessing food performance

Soft tribology can predict the oral behavior of foods and assess their performance, providing potential insights into the sensory perception of foods. This aspect is especially important in understanding complex mouthfeel characteristics like astringency, smoothness, fat perception, slipperiness, creaminess, and mouthcoating characteristics, which are crucial in food texture perception (Sethupathy *et al.*, 2021).

Challenges and future prospects

While soft tribology provides valuable insights into texture-related sensory perceptions in food oral processing, obtaining quantitative empirical relationships between physical measurements and sensory experience remains challenging (Pradal and Stokes, 2016b). The field continues to evolve, with ongoing research focused on understanding the frictional properties of foods and their relevance to sensory perception and oral processing.

In conclusion, soft tribology is a vital tool in the food industry for understanding and enhancing the sensory qualities of food products. It bridges the gap between the physical properties of foods and the sensory experience of texture and mouthfeel, thus playing a crucial role in product development and consumer satisfaction.

2.5 Saliva in soft tribology

Saliva is essential for the perception of texture and the release of flavor compounds, particularly those responsible for the perception of 'fat' in food. This release is a crucial aspect of flavor and texture experience during consumption (Feron and Poette, 2013).

Saliva plays a pivotal role in determining sensations such as creaminess, mouthfeel, and astringency in food texture perception. It is involved in oral handling processes, affecting how food textures are perceived and processed in the mouth (Laguna *et al.*, 2021).

Oral lubrication, correlated to salivary viscosity and flow rate, is crucial for the sensation of food texture and mouth-feel. This aspect is integral to how different foods are perceived in terms of smoothness and creaminess (Mo *et al.*, 2019).

The presence of saliva can modify the friction coefficient values of foods, such as yogurt, making them perceived as creamier and smoother. This alteration significantly improves the sensory perception of texture and mouthfeel (Morell *et al.*, 2017).

Variations in salivary components, particularly total protein concentration and alpha-amylase activity, have been found to correlate with the sensory perception of food texture, highlighting the importance of saliva composition in food texture analysis (Engelen *et al.*, 2007).

Artificial saliva applications in soft tribology

In addition to understanding the role of saliva, several biomimetic approaches can advance friction research in the domain of food texture perception:

Advances in soft solid tribology enable well-controlled studies that realistically mimic oral conditions, including the use of human saliva. This approach leads to progress in understanding oral processing and sensory perception (Rudge *et al.*, 2019).

Using artificial saliva in tribology studies can offer insights into lubrication behavior and contribute to understanding smoothness perception, especially in the context of oral care products (Cai *et al.*, 2017).

Dynamic tribology protocols that consider saliva's effect on lubrication and surface properties can help in understanding complex mouthfeel characteristics, like astringency and creaminess, and their variation during the eating process (Fan *et al.*, 2021).

In summary, saliva plays a crucial role in soft tribology for food texture perception, affecting lubrication, mouthfeel, and flavor release. Biomimetic advancements, such as mimicking oral conditions, using artificial saliva, and applying dynamic tribology protocols, enhance our understanding of the complex interplay between oral physiology and sensory perception of food textures. These approaches offer promising avenues for more accurate and nuanced analysis of food texture, crucial for product development and consumer satisfaction.

2.6 Tongue anatomy

The tongue's anatomy is a complex and functional aspect of the human body, playing a critical role in various activities like speech, taste, and food manipulation. Two significant types of papillae on the tongue, the filiform and fungiform papillae, have distinct functions contributing to these activities.

Filiform papillae

Filiform papillae are the most numerous papillae on the human tongue, covering most of its surface. Unlike other types of papillae, filiform papillae do not contain taste buds. Their primary function is mechanical and tactile, as they help in manipulating food within the mouth. They aid in the processes of mastication (chewing), deglutition (swallowing), and contribute to the overall texture perception of food. The presence of keratohyalin granules within these papillae also suggests a role in the protection and mechanical stress response of the tongue (Boshell *et al.*, 1980).

Fungiform papillae

Fungiform papillae, fewer in number compared to filiform papillae, are primarily involved in taste perception. These papillae are mushroom-shaped and distributed mainly on the anterior part of the tongue. Each fungiform papilla contains several taste buds, making them critical for detecting sweet, sour, salty, bitter, and umami flavors. Fungiform papillae are also richly supplied with thin and thick nerve fibers, indicating their significant role in sensory perception (Okano, 1961).

Interplay between filiform and fungiform papillae

The interplay between filiform and fungiform papillae is vital for the optimal functioning of the tongue. While filiform papillae contribute to the physical manipulation of food, fungiform papillae are essential for taste perception. This combination allows for a comprehensive sensory experience during eating, from texture and taste perception to the physical manipulation of food within the oral cavity.

In summary, filiform and fungiform papillae on the human tongue have distinct but complementary functions that are essential for the sensory and mechanical aspects of eating. Filiform papillae primarily aid in the physical aspects of eating, while fungiform papillae play a crucial role in taste perception, contributing to the overall sensory experience of food consumption. Understanding these structures and their functions is important for appreciating the complexity of human oral physiology and its impact on food perception and consumption.

2.7 Pupillometry in sensory science

Human eye

The pupil, a central feature of the human eye, plays a crucial role in vision by regulating the amount of light that enters the eye. It is the central opening within the iris, and its diameter adjustment is a critical aspect of how we respond to visual stimuli and various physiological processes. The diameter of the pupil is determined by the contraction of two antagonistic smooth muscles. These muscles work in concert to modulate pupil size in response to different stimuli.

Positioned at the edge of the iris, the circular sphincter muscle is responsible for the constriction of the pupil. It is innervated by the parasympathetic nervous system. The primary function of this muscle is to maintain the pupil in a constricted state, known as miosis, which typically ranges from 1.5 to 2 mm in diameter.

The radial muscle extends radially from the iris root to the peripheral edge of the sphincter muscle. Its role is to dilate the pupil, a process known as mydriasis, where the pupil can expand to a diameter of 7.5 to 8 mm. This muscle is innervated by the sympathetic nervous system, highlighting the balance between these two nervous systems in controlling pupil size.

A key function of the pupil is the "pupillary light reflex," a response elicited by changes in ambient light. When exposed to increased brightness, the pupil contracts to reduce the amount of light entering the eye. Conversely, in darkness or low-light conditions, the pupil dilates (mydriasis) to allow more light to enter. This reflex is crucial for protecting the retina from excessive light and optimizing vision in varying light conditions.

Pupillary fibers transmit information about incoming light from each eye to a central processing unit. This coordination ensures that both eyes exhibit the same pupil size, irrespective of the individual visual acuity of each eye.

Pupillometry

The use of pupillometry, the measurement of pupil size and reactivity, offers a promising avenue for studying emotional responses, including those related to sensory experiences such as taste. Pupillometry has a longstanding history in psychological research and is gaining traction in the sensory community as an objective tool for measuring emotional responses to products, including food.

The correlation between pupil size and cognitive effort was established by Hess and Polt (1966), indicating that increased cognitive load results in pupillary dilation. This response can be leveraged to understand the mental processing involved in sensory evaluation.

Barlow (1969) highlighted the connection between pupil size and emotional load or preference. Pupillary responses vary with emotional states, suggesting that pupil size can be indicative of emotional reactions to sensory stimuli.

Research in visual perception demonstrated that both pleasant and unpleasant images cause pupillary dilation. Similar effects have been observed in response to tactile (van Hooijdonk *et al.*, 2019), olfactory Schneider *et al.* (2009), and auditory stimuli (Bianco *et al.*, 2019). This suggests that pupillometry can be applied to various sensory modalities, including taste.

2.8 Electroencephalography in sensory science

Electroencephalography (EEG) has emerged as a valuable tool in sensory science, particularly for studying gustatory signals and their processing in the brain. This method offers excellent temporal resolution, crucial for capturing the rapid cortical activation patterns associated with taste perception. EEG records electrical signals originating from cortical postsynaptic potentials. These non-invasive measurements are obtained using electrodes attached to an EEG cap.

The EEG signals recorded from the scalp reflect the combined activity of millions of neurons firing synchronously, as described by Nunez and Srinivasan (2009). The use of digital computers has overcome past limitations of EEG, such as the small amplitude of evoked or event-related responses and background noise. By summing signals from multiple trials, event-related potentials (ERPs) can be distinguished from noise.

EEG stands as a powerful and effective method in sensory science for studying taste perception. Its ability to capture rapid changes in cortical activity, along with advancements in signal processing, makes it invaluable for understanding the complex neural mechanisms underlying our experience of taste. This method provides a window into how taste qualities, intensities, and hedonic values are encoded and processed in the human brain, offering profound insights into the neural basis of gustatory perception.

3 Materials and Methods

3.1 Sample preparation

3.1.1 Custom manufactured chocolate

Seven chocolate masses were produced, designated as 04_S0_H, 04_S18_H, 23_S0_H, 23_S9_H, 23_S18_H, 42_S0_H, and 42_S18_H. The number before 'S' represents the sucrose concentration (in weight percentage) and before "H" the hazelnut oil concentration (in weight percentage) within the total fat phase of the system. To vary the sugar content 4%-42%, sucrose was substituted with Inulin and polydextrose. The ingredients utilized for the production are listed in Table 3.1.

Materials

Table 3.1: Materials used for chocolate production.

Materials	Manufacturer
Sugar	Schweizer Zucker AG (Switzerland)
Hazelnut oil	Demeter (Switzerland)
Cacao mass "Rondo" (Ghana)	Max Felchlin AG (Switzerland)
Cacao butter	Max Felchlin AG (Switzerland)
Soy lecithin "EM04B"	Max Felchlin AG (Switzerland)
Inulin "Orafti®HSI"	BENEO-Orafti N.V. (Belgium)
Polydextrose "Litesse® Two IP"	Danisco AG (Denmark)

Mass production

The ingredients for chocolate production were proportioned as per the specified recipe (Tab.3.2). Initially, Polydextrose, Inulin, and sugar were manually blended, followed by the addition of melted cocoa mass, which was then mixed for 30 minutes. Subsequently, this mixture was transferred to a melangeur (ECGC-12SLTA, Cocoatown LLC, USA) for refining and conching, a process lasting one and a half hours. Post this phase, cocoa butter and/or hazelnut oil were incorporated into the blend, continuing the refining/conching for an additional five and a half hours, cumulating in a total of seven hours. The entire refining/conching operation was conducted within a temperature-controlled environment.

Table 3.2: Recipes of the seven chocolate masses in wt%.

	04_S0_H	04_S18_H	23_S0_H	23_S9_H	23_S18_H	42_S0_H	42_S18_H
Sugar	04.15	4.15	23.00	23.00	23.00	41.71	41.71
Hazelnut oil	0.00	6.30	0.00	3.15	6.30	0.00	6.30
Cacao mass	50.70	50.70	50.70	50.70	50.70	50.70	50.70
Cacao butter	6.30	0.00	6.30	3.15	0.00	6.30	0.00
Cacao butter (seed)	0.90	0.90	0.90	0.90	0.90	0.90	0.90
Soy lecithin	0.39	0.39	0.39	0.39	0.39	0.39	0.39
Inulin	11.83	11.83	5.55	5.55	5.55	0.00	0.00
Polydextrose	25.73	25.73	13.16	13.16	13.16	0.00	0.00

Sample production

The chocolate mass was initially preheated to 50°C. Following this, it was gradually cooled down to 34.5°C. Upon reaching this temperature, 0.9% of pre-crystallised cocoa butter (Seed Easy, LeeoTech, Switzerland) was added. The mixture was then manually stirred for 90 seconds to ensure uniform distribution.

This mass was then poured into a silicone mold, pre-warmed to 34.5°C. This was followed by manual shaking of the mold to evenly distribute the chocolate and eliminate air bubbles. Subsequently, the molded chocolate was cooled at 5°C for a duration of at least two hours.

3.1.2 Thaumatin enhanced surface structures

Five thaumatin surface masses were produced, designated as "Thaumatin 0.0", "Thaumatin 0.045", "Thaumatin 0.09", "Thaumatin 0.18" and "Thaumatin 0.36". The numbers represent the thaumatin concentration. The ingredients utilized for the production are listed in Table 3.3.

Materials

Table 3.3: Materials used for thaumatin surface mass production.

Materials	Manufacturer
Thaumatin	Penta Manufacturing (USA)
Cocoa butter	Max Felchlin AG (Switzerland)
Polyglycerol polyricinoleate	Danisco (Netherlands)
Caprylic capric triglyceride	Mibelle Group (Switzerland)
Water	Evian (France)

Mass production

To create the thaumatin surface masses, emulsions containing various concentrations of thaumatin (0, 0.045, 0.09, 0.18 and 0.36 wt%) were mixed into seeded cocoa butter. The initial step involved dissolving thaumatin in Evian water to create the dispersed phase. The composition of the continuous phase included 52 wt% caprylic capric triglycerides and 3 wt% polyglycerol polyricinoleate. The blend of the two phases was first subjected to pre-emulsification for two minutes. Subsequent emulsification was achieved in a Microfluidizer Processor (M-110EH Microfluidics, Newton MA, USA) across six cycles at a pressure of 1000 bar. The thaumatin emulsion was then mixed into seeded cocoa butter at 10 wt%.

Sample production

A custom inkjet printer (BFH, Burgdorf, Switzerland) equipped with a micro valve nozzle (SMLD 300G, Mikroventile Gyger, Switzerland) was employed for the printing process. The material was printed under a pressure of 10 bar. To ensure optimal ink viscosity and flow, the cartridge temperature was set to 32.7°C, while the nozzle temperature was slightly higher, at 32.8°C. A waiting period of 30 minutes was employed prior to printing to allow for the uniform temperature stabilization of both the ink and printer components. Precise adjustments were made to the valve opening times of the nozzle, aiming to achieve a surface patterns with a total weight of 0.10g for all samples.

3.1.3 Microfoamed surface structures

Three foamed surface masses were produced, designated as ”0”, ”50” and ”100”. The numbers represent the overrun value generated by the air inclusions. The ingredients utilized for the production are listed in Table 3.4.

Materials

Table 3.4: Materials used for foamed surface mass production.

Materials	Manufacturer
Hazelnut flavour (2015-02000-35)	Givaudan (Switzerland)
Cocoa butter	Max Felchlin AG (Switzerland)
Rapeseed oil	Florin AG (Switzerland)

Mass production

Crystallization and foaming processes were executed using a scraped surface heat exchanger (SSHE) (Schröder GmbH, Lübeck, Germany) and a dynamically enhanced membrane foaming apparatus (DEMF) (Megatron MT-MM 1-55, Kinematica AG, Switzerland). For the aroma incorporation, hazelnut flavour was mixed into rapeseed oil at concentrations of 4 wt% for the 50% overrun sample and 6 wt% for the 100% overrun sample.

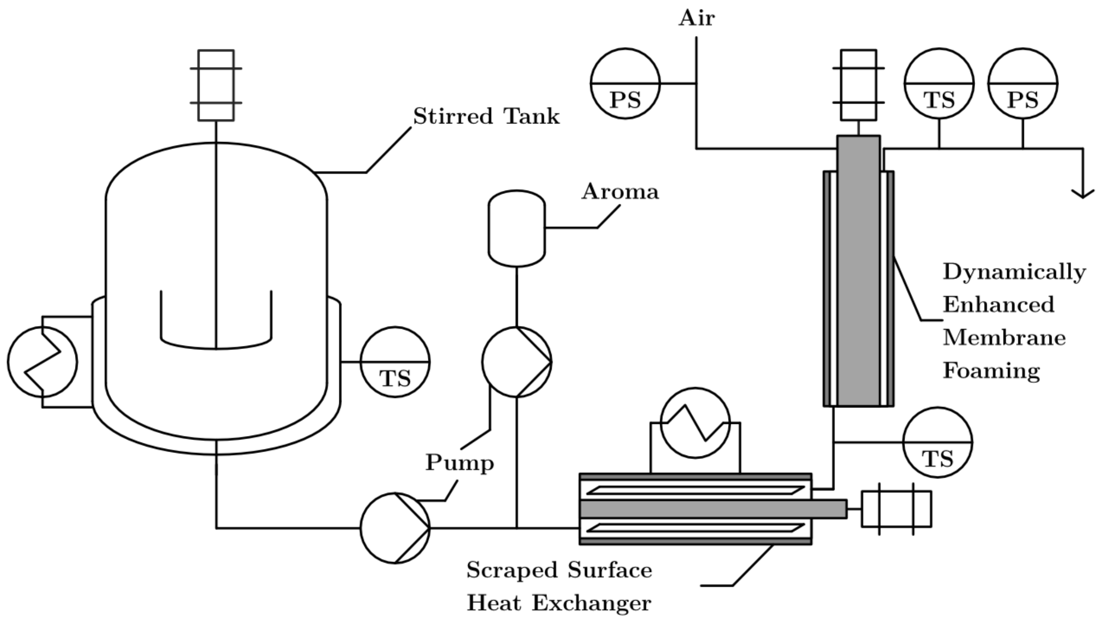


Figure 3.1: The crystallisation process and instrumentation scheme with subsequent DEMF foam formation.

Cocoa butter, maintained at 45°C, was conveyed to the SSHE at a flow rate of 125 ml/min. The SSHE operated at a temperature of 13°C and at a rotational speed of 390 rpm. At the SSHE's inlet, the aroma-oil mixture was injected into the cocoa butter at 1.26 ml/min. The ensuing crystal-melt suspension was then pumped to the DEMF. This apparatus featured a static outer cylinder with a 3.5 µm pore size and a rotating inner cylinder. Pressurized air was introduced into the DEMF at variable flow rates ranging from 180 to 300 ml/min, while rotational speeds varied from 650 to 2600 rpm. A constant temperature of 32°C was maintained in the pipelines connecting the cocoa butter tank to the SSHE, and 30°C between the SSHE and the DEMF.

RPM and flow rate parameters were finely adjusted to yield foamed masses with the targeted overruns of 50% and 100%.

Table 3.5: DEMF settings for overrun 50%, 100%

Parameter	overrun 50 %	overrun 100 %
rpm_{DEMF}	599 - 650	2600
air injection rate	180 - 190 ml/min	300 ml/min

Sample production

The same setup described for thaumatin surface masses in section 3.1.2 was used for the foamed samples. Adjustments were made to ensure optimal ink viscosity and flow. The cartridge temperature was set to 33.6°C, while the nozzle temperature was 32.5°C.

3.1.4 Neuroscientific sensory solutions

Sugar solutions of various concentrations were prepared. For the study of viscosity influence xanthan gum was added to the sugar solutions and for the hedonics study bitter solution including chinin were produced. The ingredients utilized for the production are listed in Table 3.6.

Materials

Table 3.6: Materials and their suppliers used for the neuro experiments.

Material	Supplier
Sugar	Schweizer Zucker AG (Switzerland)
Xanthan gum	Jungbunzlauer Austria AG, (Austria)
Chinin Hydrocholorid Dihydrat	Roth AG (Switzerland)
Citric acid monohydrate	FloraCura Health (Germany)
Evian water	Danone, Paris, France

Sample production

Sucrose solutions of 0 wt%, 10 wt%, 20 wt%, 30 wt%, 40 wt% and 50 wt% were produced by mixing sugar with Evian water until dissolved.

For the viscosity study two sweetness levels at 0 wt% and 20 wt% sucrose were adjusted by adding 0.25wt% xanthan gum to generate samples of same sweetness load but increased viscosity. The solutions were stirred until disolved.

For the hedonics study two different tastant solutions at two concentrations were produced. The bitter sample at low and high intensity had 0.0097 wt% respectively 0.0235 wt% of added quinine hydrochloride dihydrate. The sweet solutions in low intensity had 3.127 wt% sucrose with 0.024wt% citric acid and at high intensity 31.285 wt% sucrose with 0.211 wt% citric acid. The citric acid was added to improve the hedonics of the sweet solutions resembling soft drinks. The solutions were stirred until disolved.

3.2 Material characterization

3.2.1 Melting behavior

The melting behavior was examined using a differential scanning calorimeter (DSC 3+ / 500, Mettler Toledo GmbH, Switzerland). To calibrate the instrument, a 6.432 mg indium sample was employed. For the experimental measurements, each sample, weighing 5 mg ±0.5 mg, was placed into an aluminum crucible (Mettler Toledo GmbH, Switzerland). An empty crucible was utilized as a reference.

Initially, each sample was tempered at 20°C for 20 minutes. Subsequently, the samples were heated at a rate of 4 K/min up to 50°C. To ensure data reliability, each sample underwent triplicate measurements.

3.2.2 Particle size distribution

To analyze particle size distribution, a laser diffraction measuring device (13 320 XR, Beckman Coulter Inc., USA) was employed. The experimental procedure involved suspending a few drops of chocolate in Hydriol® SOD.24 (Hydrior AG, Switzerland), followed by ultrasonification at 65 Hz for 120 seconds to deagglomerate the sample. Measurements were conducted based on the Frauenhofer theory. The d90, d50, and d10 values were directly calculated by the device's integrated software and utilized to determine the span as defined in Equation 3.1. Each sample was measured in triplicate to ensure data consistency. Furthermore, a normalization of the obtained data was performed through bandwidth correction. This normalization process entailed dividing the volume density in a specific class by the cumulative density, with the volume density calculated by dividing the frequency by the respective class width.

$$span = \frac{d_{90} - d_{10}}{d_{50}} \tag{3.1}$$

3.2.3 Flow behavior

Rheological measurements were conducted using a rheometer (MCR 302, Anton Paar, Austria) with a couette geometry (CC27, Anton Paar Austria). The experiments were shear controlled and performed in a logarithmic shear range of $0.1s^{-1}$ to $1000s^{-1}$. Each decade, ten points were measured when reaching steady state.

Sample differences included for chocolate samples an equilibration step at 40°C for approximately 10 minutes followed by preshearing at $10s^{-1}$ for 120 seconds. The neuroscientific sugar solutions were measured at 35°C. All measurements were done as triplicates.

3.2.4 Tribology

Molten state

The molten tribology measurements were conducted using a rheometer (MCR 702, Anton Paar, Austria) with a Ball on Three Pins (BTP) tribology cell and CTD180 temperature control unit (Anton Paar, Austria). The tribosurfaces used were a glass ball with a diameter of 0.127m (BC12.7, Anton Paar, Austria) and three polydimethylsiloxane (PDMS) pins (Sylgard 184, Dow Corning, USA).

Before starting the measurement, the sample was held at 35°C for 30 min. All chocolates were analyzed at a normal force of $F_{N,tribo}$=0.2 N. The friction force was measured as a function of the sliding velocity between 10^{-8} m/s and 0.1 m/s. Each sample was measured ten times with an alternating increasing and decreasing speed ramp. Following the recommendation of Anton Paar, the initial two measurements were excluded from the analysis. This decision was based on the observation that during the first runs, the tribosurfaces experience a 'running-in' effect. This effect involves the surfaces conforming to each other, which may occur through wear, plastic deformation, or a combination of both. It is widely accepted in the field that the third and subsequent runs provide a more accurate representation of the system's frictional behavior (Pondicherry *et al.*, 2018).

Solid state

A custom ring geometry to mimic an in vivo melting process of chocolate was designed. The solid setup is composed of an upper sample holder geometry and the default metal heating plate (P-PTD 200, Anton Paar GmbH, Austria) as the bottom geometry. The holder was 3d printed with PLA and mounted to a standard Anton Paar measuring shaft. Images of the setup can be seen in Figure 3.2. Noah

Kessli one of my master thesis students was heavily involved in the developement of the geometry. Theses images were taken by him and presented in more detail in his thesis.

The sample holder had an inner radius of r_{in}=1.1cm and an outer radius of r_{out}=1.8cm. The sample had the same radi and a height of 1.5cm. The friction measurements of the solid state geometry were performed at F_N=40 N to ensure the same contact pressure compared to the molten setup. The same sliding velocity range as in the molten measurements was used. The samples were analysed at 35°C. Since the sample melted during the measurement, only one run per sample was conducted.

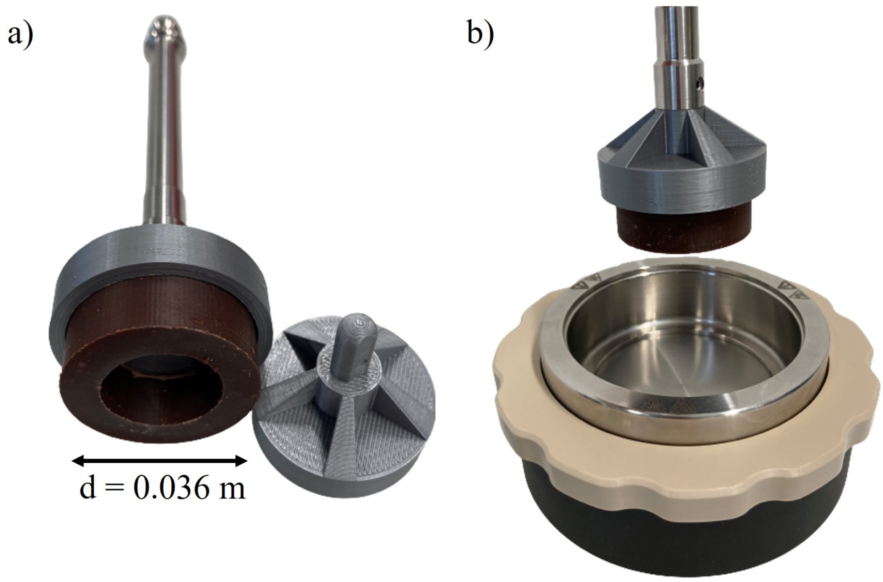


Figure 3.2: a) upper custom solid geometry b) with lower P-PTD 200 heating unit. Images by Noah Kesseli.

Biomimetic tribosurfaces

For the study with biomimeticly enhanced tribosurfaces new PDMS pins had to be produced. All steps involved in their production are presented below:

Tongue characteristics aquisition followed the recommendations of the Denver Papillae Protocol (Nuessle *et al.*, 2015). Pictures of participants' tongue surfaces were taken after staining the surface with brilliant blue food colorant (Trawosa AG, Switzerland). The colorant was diluted before application in water with 0.0278 wt% concentration. The participant took a sip of the colored solution and rinsed the whole mouth for 1 min, staining the filiform papillae.

Figure 3.3: Acquired tongue surface image highlighting the coloration. Paper cutout placed on tongue as size reference.

The fungiform papillae remained their natural red color, thus counting was made distinctly easier. The positions and sizes of the fungiform papillae were recorded for later calculations.

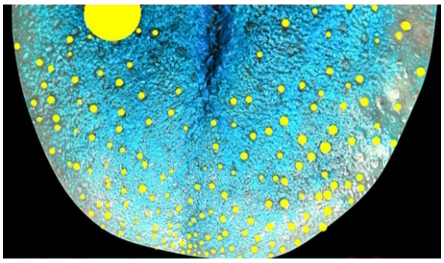


Figure 3.4: Manual counting of fungiform papillae highlighted in yellow.

The images were then segmented by fitting the contour of the tongue edge and seperating the tongue surface into zones. For each zone the pixels present were checked for blue color thus marking them as filiform papillae. The fungiform papillae were segmented by reading their recorded coordinates and matching if they fall into a segment.

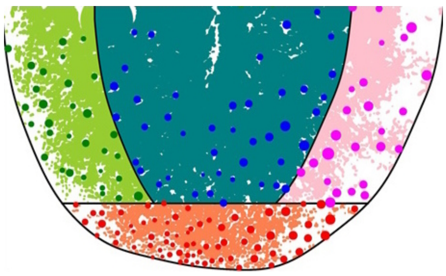


Figure 3.5: Segmentation of the tongue surface.

For each segment the blue pixel sum of filiform papillae was used to calculate its area density. And for fungiform papillae their coordinates were combined with the recorded diameter data allowing the calculation of the specific density.

With these densities and the height data of average papillae taken from the study of Andablo-Reyes *et al.* (2020), a 3d-model of tongue surfaces were created in Python.

The code distributed points on a defined surface area trying to match the numeric density calculated from the tongue images. During this distribution the code checked if the placed new papillae is inside the proximity of an already place papillae. This proximity range was defined as the average radius of the papillae, thus guaranteeing that no overlapping occured during distribution.

After distribution onto the 2d surface a 3d shape was generated at each papillae point. The height was matched based on the study of Andablo-Reyes *et al.* (2020) and a paraboloid dome surface was fitted at each papillae point. Thus generating a 3d surface structure resembling the size and shape of natural papillae.

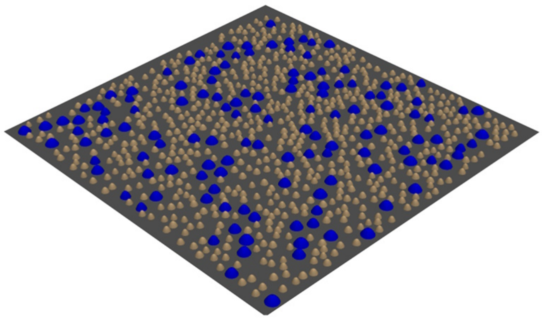


Figure 3.6: Computer generated tongue surface.

Final step included creation of a negative mold including this new surface using a stereo lithography (SLA) printer (Original Prusa SL1S speed, Prusa, Czech Republic). New tribopins were then produced by pouring PDMS into this mold. And after curing them for 3 hours at 70 C° they were ready to be used in the biomimeticly enhanced tribological measurements.

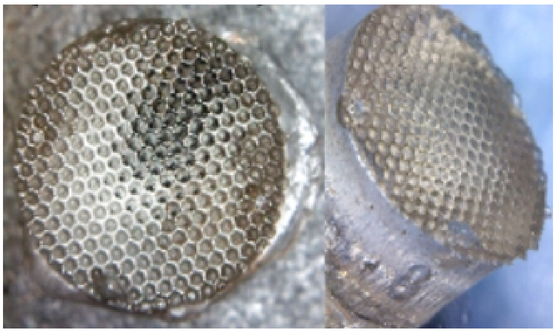


Figure 3.7: PDMS pins with structured surface.

3.3 Sensory evaluations

3.3.1 Custom manufactured chocolate

Assessment

To assess variations in sweetness, bitterness, and smoothness, panellists were asked to indicate the maximum intensity they perceived for each attribute. Attribute definisions are listed in Table 3.7. The evaluation process commenced with a reference chocolate sample. For all attributes — sweetness, smoothness, bitterness — the reference intensity was standardized at 50. After tasting this reference, the panellists sampled other chocolates and compared them to the reference, assigning a perceived intensity on a scale from 0 to 100. Two testing sessions were carried out.

All evaluation sessions took place in the sensory laboratory at the Bern University of Applied Sciences in Zollikofen (HAFL). These sessions were conducted under the supervision of a panel manager, Saskia Mantovani, and utilized the EyeQuestion software (version 4.11.20) for data collection and management.

Training

Beforehand three training sessions were conducted to familiarize the panellists with the rating scale for sweetness and smoothness. For sweetness calibration, different sugar solutions were used, as detailed in Table 3.8. The sucrose concentrations in these solutions were based on the guidelines proposed by Karalus *et al.* (2020). To train for smoothness, chocolate samples 23_S0_H and 23_S18_H, which differed in conching time (see Table 3.9), were utilized. The conching times selected for the smoothness calibration were determined by the author.

Table 3.7: List of attributes and their meaning.

Attribute	Definition
Sweetness	Intensity of basic taste sweet (sucrose in water)
Bitterness	Intensity of basic taste bitter (caffeine in water)
Smoothness	Structure of sample surface evaluated when moving the tongue

Table 3.8: Recipes of solutions used in sweetness attribute training.

	sucrose [g/100 ml]	cacao [g/ 100 ml]
slightly less	3	2.5
little less	4	3.5
reference	5	3.5
little more	6	3.5
slightly more	7	3.5

Table 3.9: Change in conching time of chocolate samples used in smoothness attribute training

Masses	conching time [h]	smoothness rating [-]
23-0	1.5	10
23-0	7	40
23-9	7	50
23-18	7	60
23-18	12	75

Panel

8 female panelists, aged between 35 and 55 years, were recruited for the sensory evaluation. The selection of participants was not based on gender or age and just a random process. During the sessions, seven of these women were consistently present, while one panelist had to be replaced due to symptoms of Covid-19.

Consumption protocol

The protocol for chocolate consumption during these sessions was defined as follows:

"Place the sample in your mouth and press it lightly against the palate so that the sample is stabilised and does not tip over. It is allowed to move the tongue in regular circular motions to facilitate the sample's melting. As soon as the sample no longer adheres, the sample can also be rotated. If necessary, swallowing is allowed. In the end, the sample must be swallowed completely".

To ensure a neutral palate between samples, the panelists were instructed to rinse their mouths with lukewarm water and consume a "Microc" cracker (Migros, Switzerland) following each chocolate sample. After this, a waiting period of 90 seconds was implemented before proceeding to taste the next sample.

Statistical evaluation

The results obtained from the sensory tests were subjected to a one-way analysis of variance (ANOVA), with sweetness, bitterness, and smoothness designated as the dependent variables. The samples, panelists, and sessions were considered fixed factors. For mean comparison, Tukey's Honestly Significant Difference (HSD) test was employed. All data analyses were conducted using the integrated analysis tools in Origin software. A p-value of less than 0.05 was set as the criterion for statistical significance.

Sample design

The samples during sensory analysis of chocolates were cubes of dimensions 16.0mm x 9.6mm x 12.8mm.

3.3.2 Thaumatin enhanced surface structures

Assessment

All sensory evaluation sessions were conducted at the panelists' homes over a period of three weeks. This limitation was due to the Covid-19 restrictions.

The sensory evaluation included two test sessions. The samples were rated for their sweetness intensity on a scale from 0 (unsweet) to 100 (extremely sweet).

Each sensory session commenced with a warm-up sample, specifically chosen for its known sweetness intensity, which was calibrated at 50 - representing the midpoint of the scale bar. This practice was intended to acclimate the panelists to the range of sweetness intensities they would be evaluating, thereby ensuring a consistent frame of reference from the outset of each session

During the test session, all samples had to be tested. The order of the samples was balanced for every panelist to prevent any sample effect.

Training

Four training sessions were included in this sensory evaluation. The samples used in training were "Thaumatin 0" for rating 10, "Thaumatin 0.09" for rating 50 and "Thaumatin 0.36" for rating 90.

The training sessions were designed to acquaint the panelists with both the test protocol and the nuances of rating sweetness intensity on the scale bar. During the initial two sessions, the focus was solely on rating the maximum sweetness intensity. To delineate the scale's boundaries, two samples with pre-determined sweetness intensities of 10 and 90 were tasted at the start, representing the lower and upper limits of the scale. Furthermore, the panelists were presented with two additional samples of unknown sweetness intensities, which they were tasked to rate on the scale bar. At the conclusion of these sessions, the EyeQuestion software provided immediate feedback on the accuracy of their ratings.

In the third and fourth training sessions, the concept of progressive profiling was introduced. This required the panelists to not only assess the maximum perceived sweetness intensity (max) but also to evaluate the initial (start) and final (end) sweetness intensities of the samples.

Panel

The 14 panelists of the sensory assessment consisted of seven women and seven men who were between 23 and 36 years old.

Consumption protocol

The protocol for chocolate consumption during these sessions was defined as follows:

Please place the probes with the dots directed longitudinally on the anterior half of your tongue. Start the sensation by gently pressing the probe to the palate without biting it. Use your tongue by moving it periodically to enhance the melting. Swallow normally if required. the sensation has ended once the whole sample has been swallowed. After each probe rinse your mouth with lukewarm water and if necessary a cracker. Try to repeat the same cycle for each probe tested.

To maintain the quality and integrity of the samples throughout the sensory evaluation, they were stored in a refrigerator. The samples were then taken out and allowed to acclimatize at room temperature for 30 minutes prior to each session. To ensure a consistent sensory experience, a thorough rinsing protocol was followed between the tasting of each sample. This protocol involved the consumption of 'Microc' crackers (Migros, Switzerland) and lukewarm water.

Statistical evaluation

The results obtained from the sensory tests were subjected to a one-way analysis of variance (ANOVA), with sweetness designated as the dependent variable. The samples, panelists, and sessions were considered fixed factors. For mean comparison, Tukey's Honestly Significant Difference (HSD) test was employed. All data analyses were conducted using the integrated analysis tools in Origin software. A p-value of less than 0.05 was set as the criterion for statistical significance.

Sample design

For this sensory sessions, 12 samples were produced. All samples were designed to have the same absolut thaumatin load except the uniform samples used for scale training. The design idea was to oberve pattern effects in perception.

- Uniform: 5 samples with 184 dots of different thaumatin concentration (0, 0.045, 0.09, 0.18 & 0.45 wt% of surface mass) - a)

- Bulk: Thaumatin distributed in chocolate base. The 184 printed dots did not contain any sweetener. a)
- Layer: Covered with a thin layer of 0.09 wt% thaumatin instead of being printed. The layer had the same mass as 184 dots. b)
- Half: Pattern of 92 dots, with 0.18 wt% thaumatin. c)
- Quarter: Pattern of 46 dots, with 0.36 wt% thaumatin. d)
- Chess: 184 dots of which 92 had 0.18 wt% thaumatin and 92 had 0 wt% thaumatin. e)
- Center: 184 dots with 92 in the center with 0.18 wt% thaumatin and 92 at the ends with 0 wt% thaumatin. f)
- Periphery: 184 dots with 92 at the ends with 0.18 wt% thaumatin and 92 in the center with 0 wt% thaumatin. f)

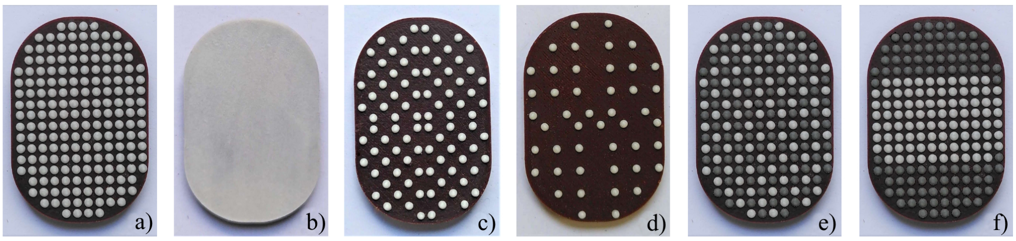


Figure 3.8: Visuals of the thaumatin enhanced surface samples (a) Uniform/Bulk (b) Layer (c) Half (d) Quarter e) Chess f) Center/Periphery.

3.3.3 Microfoamed surface structures

Assessment

Two testing session without training were conducted. No training was needed because in this sensory evaluation the Two-Alternative Forced Choice (2AFC) method was used. Central to this methodology is the principle that a panelist is comparing each trial two samples and is tasked with identifying a particular difference between them. The panelist is unaware of the specific difference and must choose the sample that appears to exhibit more of the targeted attribute.

In this study the attributes were sweetness and hazelnut aroma. The panelists were presented with different comparison pairs and had to choose the sample which they percieved higher for both attributes. All possible pairs appeared equally often.

Panel

22 panelists were recruited for this sensory evaluation.

Consumption protocol

The protocol for chocolate consumption during these sessions was defined as follows:

Please place the probes with the dots directed longitudinally on the anterior half of your tongue. Start the sensation by gently pressing the probe to the palate without biting it. Use your tongue by moving it periodically to enhance the melting. Swallow normally if required. the sensation has ended once the whole sample has been swallowed. After each probe rinse your mouth with lukewarm water and if necessary a cracker. Try to repeat the same cycle for each probe tested.

Statistical evaluation

The proportion of choice obtained from the sensory tests were subjected to a binomial test. All data analyses were conducted using the integrated analysis tools in Origin software. A p-value of less than 0.05 was set as the criterion for statistical significance.

Sample design

For this sensory sessions, 4 samples were produced. All samples are designed to have the same absolut aroma load. The samples were all visually equal with 184 dots evenly distributed on the chocolate surface, resembling the "Uniform" sample from the thaumatin study described above.

- Sample "100": Surface mass had an overrun of 100%
- Sample "50": Surface mass had an overrun of 50%
- Sample "0": Surface mass had an overrun of 0%
- Bulk: Aroma distributed in chocolate base. The 184 printed dots did not contain any aroma.

3.3.4 Neuroscientific sensory

The sensory trials were conducted at the Decision Neuroscience Laboratory at ETH Zurich. The study received approval from the Swiss Association of Research Ethics Committees (BASEC 2021-02420).

Experimental set-up

Liquid samples were precisely administered using a custom-designed gustometer. The samples were stored in reservoirs, which were maintained under specific pressures. These reservoirs were connected to electric valves via plastic tubing, with the entire system being computer-controlled for accurate operation. For delivery of each sample, the corresponding valve was opened for a duration of 0.25 seconds, ensuring precise deposition of the sample into the participant's mouth.

Given the varying viscosities of the solutions, different reservoir pressures were set to guarantee a consistent volume of 0.4 ml per trial. Prior to the start of the sensory session, a calibration of the setup was performed.

To minimize spatial variations in the delivery of samples onto the tongue, mouthguards typically used in boxing were used. Participants were instructed to customize their mouthguards for a personalized fit. Once tailored, small dosage needles were carefully punctured into these mouthguards. These needles were then connected to the gustometer using plastic tubes. This setup ensured that the liquid samples were delivered consistently to the same area of the tongue for each participant.

The experiment consisted of five training sessions and one experimental session.

Training sessions

The first session was dedicated to calibrating the customized mouthguard, ensuring that the solutions were accurately applied to the tip of the tongue. This calibration was crucial for the consistency of the sensory evaluations. The second session focused on scale training, where participants were presented with samples that corresponded to sweetness intensities of 10 and 90 on the rating scale. This exercise aimed to familiarize them with the range of the scale. In the subsequent training session, participants were given a sample with an undisclosed level of sweetness, which they had to rate on the scale, enhancing their proficiency in sweetness evaluation. The fourth session was devoted to calibrating the eye tracker used for pupilometry. The final training session served as a refresher, revisiting the anchor points on the scale to reinforce the participants' understanding and memory of the range of sweetness intensities.

Testing session

During the experimental task, participants were asked to rate both the hedonic qualities or the perceived intensities of the samples. They were allowed to move their tongues naturally, with the caveat that they do so as consistently as possible to ensure uniformity in sample evaluation. However, in trials specifically designed to observe the influence of the consumption protocol, tongue movement was deliberately restricted for half of the trials to assess its impact on taste perception.

To maintain focus and minimize external auditory distractions, participants were equipped with earplugs. After sampling, they were permitted to rinse their mouths as needed to eliminate any residual taste sensations. This procedure was vital to prevent carry-over effects from one sample to the next, ensuring accurate and isolated assessments of each sample. After completing 20 trials, participants were given the opportunity to take a short break. This was an essential step to ensure their comfort and maintain their focus throughout the experimental session. The presentation of the samples during the experiment followed a random yet evenly distributed pattern, to avoid any order effects that could influence the participants' responses. Upon conclusion of the experimental task, participants were requested to complete a questionnaire. This questionnaire included queries related to demographic information and their sugar consumption habits. The inclusion of these questions was aimed at gaining insights into individual differences that could potentially influence taste perception and preferences."

The hedonics experiment was structured somewhat differently, though the initial training tasks were conducted in the same manner as previously described. The experimental task itself was split into two distinct parts. In the first part, the participants' pupil sizes were recorded without requiring them to rate the solutions. This approach was designed to observe the participants' unmediated physiological responses to the samples. Following the scale training, the second part of the experimental task commenced, wherein participants were asked to rate the solutions. To ensure consistency and comparability of results, all participants performed these tasks in the same predetermined sequence.

Panel

The participants were thoroughly informed about the nature and objectives of the experiments and each participant was provided with a consent form. To ensure the integrity of the sensory data, recruits were instructed not to smoke, eat, or drink anything except water in the hour preceding the experiment.

- In the consumption protocol study 49 subjects were enrolled, 23 men 26 women.
- In the viscosity experiment 26 subjects were enrolled, 12 men and 14.
- For the hedonics experiment 27 subjects, 9 men and 18 women were enrolled.

Analysis

The results obtained from the sensory tests were subjected to a one-way analysis of variance (ANOVA), with sweetness designated as the dependent variables. The samples and panelists were considered fixed factors. For mean comparison, Tukey's Honestly Significant Difference (HSD) test was employed. All data analyses were conducted using the integrated analysis tools in Origin software. A p-value of less than 0.05 was set as the criterion for statistical significance.

3.4 Pupillometry

Data collection

Pupil size was measured utilizing the EyeLink 1000 Plus eye tracker (SR Research, Ottawa, Canada), with a sampling rate of 1000Hz. To ensure the precision of the data, the eye tracker was individually calibrated for each participant. This step was crucial for capturing the unique eye characteristics of each participant and accurate calculation of gaze points.

During the task, participants were positioned in front of a computer screen, with their chins resting on a chin-rest. This arrangement was designed to minimize head movements, thereby enhancing the accuracy of the eye tracker. The screen's color settings were adjusted to a low contrast to diminish the pupillary light reflex, which could otherwise influence the pupil size readings. Participants were instructed to maintain their gaze on a fixed cross in the center of the screen and to avoid blinking during the testing phase. This approach was essential to ensure uninterrupted and accurate pupil size measurements. Following the completion of the testing phase, participants were allowed to blink and freely move their eyes.

Pre-processing

Pre-processing was based on the protocol proposed by Kret and Sjak-Shie (2019):

1. Removal of dilation speed outliers
2. Filtering of edge artefacts

3. Removal of samples that were flagged as blinks by the eye tracker
4. Removal of samples that fall outside a feasible range of pupil diameters (0.5 - 9mm)
5. Exclusion of clusters of valid samples less than 40ms in length, if surrounded by data gaps greater than 50ms
6. Interpolation of gaps smaller than 300ms
7. Smoothing of pupil data with a zero-phase low-pass filter

Analysis

The pre-processed data from the eye tracker underwent a series of adjustments, including baseline correction and z-scoring. To establish a reference for baseline pupil size, a 500ms time window prior to the onset of each stimulus was defined. The average pupil size calculated within this window served as the baseline. Subsequently, this mean value was subtracted from all subsequent data points in the respective trial to obtain baseline-corrected data.

For analysis linear mixed-effects models were employed to establish correlations between the pupil data and various factors such as rating, sample concentration, and study condition. This modeling approach allowed for the accommodation of both fixed and random effects, thereby providing a comprehensive understanding of how these variables influenced pupil responses. The calculations and statistical analyses were conducted using MATLAB (MathWorks Inc, USA).

3.5 Electroencephalography

Data collection

In the experiment designed to measure the brain response to sensory cues, electroencephalography (EEG) data were captured at a frequency of 500Hz. This was accomplished using a high-density EEG cap, equipped with 129 electrodes, to ensure comprehensive brain activity mapping. For optimal signal quality, the cap was carefully positioned on each participant's head, and each electrode was filled with a conductive gel. The gel played a crucial role in enhancing skin conductivity, thereby reducing electrical resistance and improving the quality of the readings.

Before starting with the EEG recording, a thorough check of the impedance of the electrodes was conducted. The target was to achieve an impedance value below 50Ω, as lower impedance values are indicative of better signal quality and reliability.

This preparatory step was critical to ensure that the EEG data collected were of the highest quality needed for uncovering significant correlations.

Pre-processing

Pre-processing was performed using the Fieldtrip toolbox (Oostenveld *et al.*, 2011), EEGLAB (Delorme and Makeig, 2004) and Automagic (Pedroni *et al.*, 2019) in MATLAB (MathWorks Inc, USA) including:

1. Data downsampling to 250Hz
2. High-pass filtering at 0.1Hz
3. Low-pass filtering at 45Hz with hamming filters
4. Bad channels identifcation with clean raw data plugin
5. Removing of artefacts with IClabel (Pion-Tonachini *et al.*, 2019)

Components that were estimated to be muscle, eye movement, heart, line noise or channel noise artefacts with a probability higher than 85% were removed.

Analysis

All event-related potentials (ERPs) in this study were subjected to baseline correction. This was achieved by subtracting the average value recorded from 200ms before the stimulus onset until the onset itself.

Following this, a correlation analysis was conducted at each time point, correlating the EEG data with the participants' ratings. This process involved computing regression coefficients for each participant, which were then aggregated to determine the correlation significance at the group level. Given the extensive nature of the data, a robust approach to correct for multiple comparisons was employed, specifically a cluster correction method. This involved identifying data points, defined by time and channel, where correlations reached a 0.05 significance level. Clusters of these significant data points were then formed by locating adjacent significant points in either space or time.

To validate these findings, the analysis was repeated with shuffled data to establish a null distribution. This step was crucial for determining the cluster size that would likely occur by chance at a level of 0.05%. Clusters falling below this threshold size were considered statistically insignificant. This rigorous approach ensured that only clusters of significant size, unlikely to be due to random variation, were identified as meaningful in the context of the study.

4 Texture and taste perception of chocolate

In this chapter the primary focus lies in unraveling how the physical properties of chocolate, such as viscosity, particle size, melting behavior and mainly friction response, influence its perceived sweetness, bitterness and a particular focus on smoothness.

The tribological measurements, employing both standard and custom-designed setups, provide a deep dive into the frictional characteristics of chocolate under conditions that mimic human consumption. The aim was the enhancement of the method to increase the realism of the tribological measurements. This approach offers valuable insights into how chocolate's textural attributes interact with the human oral environment during consumption.

Furthermore, the chapter presents an innovative investigation into the role of the tongue's microstructure in sensory perception. By mimicking the topography of different tongue regions, the study sheds light on the complex dynamics between the physical properties of chocolate and the physiological characteristics of the human tongue. Through a combination of sensory panel evaluations and advanced tribological analyses, this chapter provides a comprehensive insight of how the physical texture of chocolate correlates with sensory experiences. The findings not only contribute to the scientific knowledge of food texture and sensory perception but may also hold significant implications for the chocolate industry, guiding the development of products that could cater to more detailed consumer preferences.

4.1 Custom manufactured chocolate

Starting with investigating the correlation between the sensory perception of various custom manufactured chocolate masses and their analytically measured material properties. The goal is to deepen the understanding of how recipe modifications affect human perception. Seven distinct chocolate masses, produced at ETH Zürich, underwent sensory analysis through comparative profiling, focusing on "sweetness," "bitterness," and "smoothness,".

4.1.1 Analysis of sensory responses

Sweetness

In the assessment of sweetness shown in Figure 4.1, panelists' ratings significantly differed among samples, showing a trend of increased scores with higher sugar content. While this finding aligns with general expectations (Guinard and Mazzucchelli, 1999), its empirical validation is crucial for the study, given the role of sugar content as one of the main variations in the recipes. Additionally, analyses of samples with identical sugar but varying hazelnut oil content also revealed an enhanced sweetness perception. This observation underscores the influence of changing sugar content on enhancing sweetness in chocolates, and further suggests that increasing hazelnut oil content can similarly augment this perception. Notably, between samples 23_S18_H and 42_S0_H, no significant difference in sweetness is detectable despite differing almost double in sugar content. This indicates that manipulating hazelnut oil content can elevate the sweetness perception in samples with lower sugar to levels comparable to those with higher sugar load. At the lowest sugar concentration where the well documented masking effect of bitterness by sugar is reduced (Walters, 1996), the influence of oil is not observed. This suggests that at such levels, other factors like bitterness perception may be more dominant, overshadowing the oil's effect.

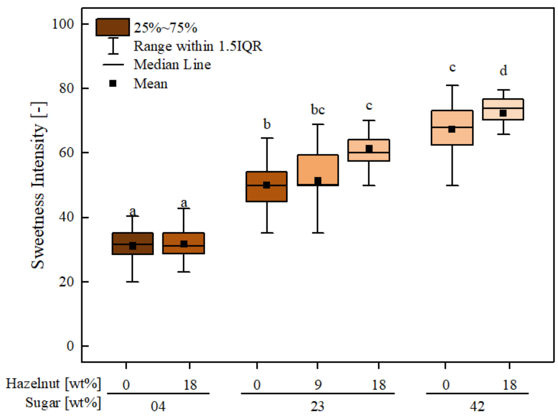


Figure 4.1: Perceived sweetness intensity during comparative profiling (8 panellists in two sessions). Sugar and hazelnut oil concentration are indicated in wt%. Samples that do not share a letter are significantly different at the 0.05 level.

Bitterness

In Figure 4.2 similar significant differences are noted in bitterness perception among the samples. The study confirms the masking effect of sugar on bitterness, with lower bitterness scores in samples with higher sucrose content (Guinard and Mazzucchelli, 1999). The presence of oil appears to further enhance this masking effect. However, at the lowest sucrose levels, no significant differences in bitterness perception are observed, indicating deviations from the general trends and necessitating further investigation beyond this thesis.

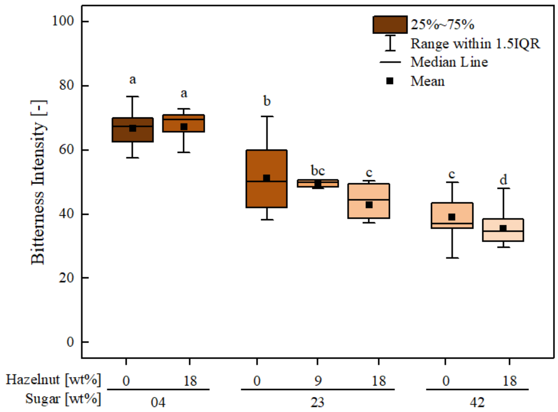


Figure 4.2: Perceived bitterness intensity during comparative profiling (8 panellists in two sessions). Sugar and hazelnut oil concentration are indicated in wt%. Samples that do not share a letter are significantly different at the 0.05 level.

Smoothness

The attribute of smoothness presented in Figure 4.3 also follows a similar pattern. An increase in smoothness perception correlates with higher sugar and hazelnut oil content, and significant differences are noted between the samples. The role of oil as a lubricant, reducing friction, explains its impact on smoothness. A study by Upadhyay and Chen (2019) found that higher oil mass fractions in oil-in-water emulsions lead to a hydrodynamic regime influencing smoothness perception. In addition, a study by Kistler *et al.* (2021) found that sugar increases the perception of smoothness and viscosity in products such as confectionery and beverages. Higher sugar concentrations are generally perceived as smoother and more viscous.

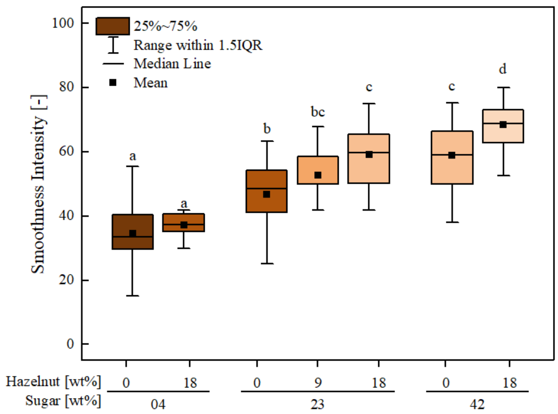


Figure 4.3: Perceived smoothness intensity during comparative profiling (8 panellists in two sessions). Sugar and hazelnut oil concentration are indicated in wt%. Samples that do not share a letter are significantly different at the 0.05 level.

4.1.2 Characterization of physical properties

The chocolate masses underwent characterization through a series of analytical techniques. Rheological measurements were employed to provide insights into their flow properties, revealing how each chocolate behaves under various shear conditions. Calorimetry was utilized to elucidate their melting behavior, offering a quantitative perspective on the thermal transitions, such as melting points, that these chocolates undergo. Additionally, laser diffraction was applied to characterize the particle size distribution, enabling a detailed understanding of the size range and uniformity of particles within each chocolate mass. These methodologies lead to a comprehensive collection of the physical and thermal properties of the chocolate masses, contributing to a more nuanced understanding of their sensory attributes.

Flow behavior

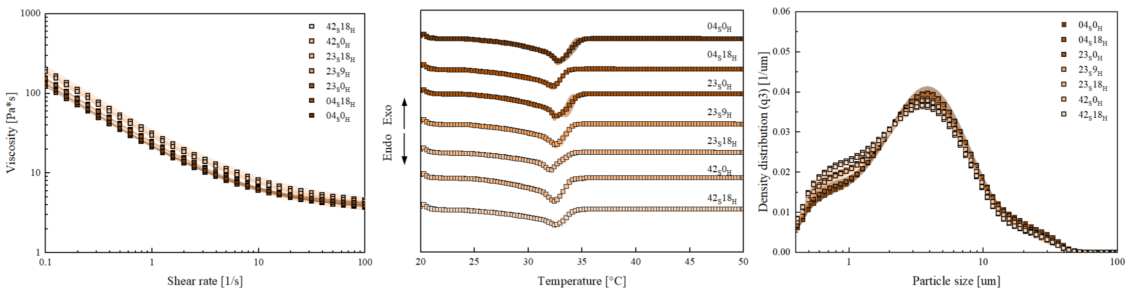
The flow curves shown in Figure 4.4a obtained from rheological measurements displays shear thinning behavior, a characteristic typically observed in chocolate (Glicerina *et al.*, 2013). This reflects the complex structural interactions within the chocolate masses. Understanding this flow behavior is crucial for comprehending how chocolate behaves during consumption, influencing factors like mouthfeel and texture and allowing a deeper understanding of the smoothness attribute.

Melting behavior

Irrespective of variations in hazelnut oil or sugar content, each chocolate mass displayed a single melting peak within the temperature range of 32 - 34 °C, as observed through calorimetric analysis (Fig.4.4b). The uniformity of this melting characteristic across all samples suggests that each chocolate mass possesses sensory attributes commonly associated with well-tempered chocolate.

Particle size distribution

All chocolate masses demonstrated a monotonic size distribution pattern, as revealed by the laser diffraction analysis (Fig.4.4c). The uniformity in this aspect across the different samples was crucial for ensuring that any variations in smoothness perception were not influenced by differences in particle size distribution.



(a) (b) (c)

Figure 4.4: Sample characterization (a) viscosity curve at 40°C using a couette geometry. (b) DSC curves. (c) particle size distribution. Samples indicate "S" sugar conc. and "H" hazelnut oil conc. Standard deviations are colored around the mean value. N = 3.

4.1.3 Correlation of material properties and sensory attributes

In Figure 4.5 a correlation analysis between the material properties of the chocolate masses and the sensory results is presented. This analysis reiterates the significant relationship between sugar content and the three sensory attributes. Specifically, sweetness and smoothness show a positive correlation with sugar content, whereas bitterness exhibits an inverse correlation.

The sensory attribute of smoothness was not influenced by the particle size distribution or the melting behavior of the chocolates. This observation suggests that these material properties do not play a pivotal role in determining the perception of

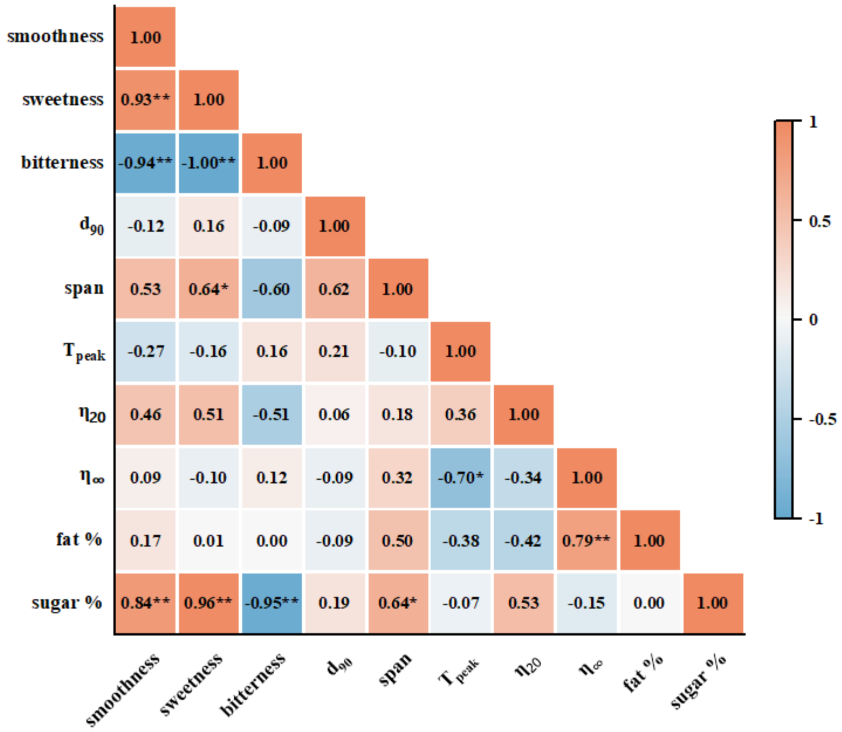


Figure 4.5: Correlation table with correlation coefficients comparing sensory evaluations to material properties. ** refers to a significance level of 0.01 and * to a significance level of 0.05.

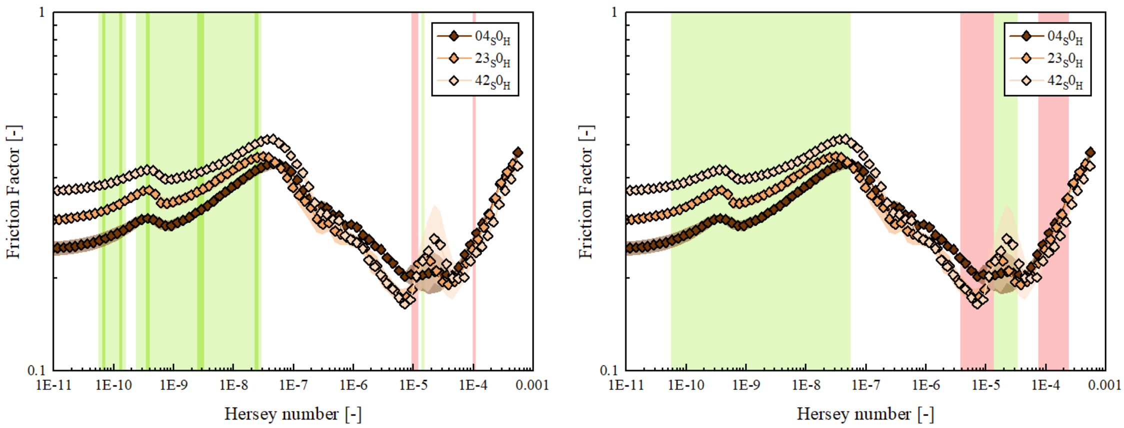
smoothness in the presented samples. Furthermore, the viscosity of the chocolate, while a key textural property, did not account for the variance in smoothness scores. This discrepancy indicates that there are additional factors at play, prompting a deeper exploration into the role of friction in textural sensory perception. Qian *et al.* (2020) reported that cocoa concentration significantly affects the smoothness of chocolates, suggesting that viscosity alone may not be a sufficient method for evaluating smoothness. In the study's sample cocoa content was kept constant but this finding implies that other textural properties besides viscosity can contribute to the perception of smoothness in chocolate.

4.1.4 Analysis of friction behavior and texture perception

The above findings highlight the complexity of sensory perception in chocolates, where multiple physical properties interact in nuanced ways to influence how chocolate is experienced by consumers. This complexity underscores the need for further research, particularly in understanding how friction contribute to the texture and mouthfeel of chocolate. Such investigations should reveal new insights into the formulation and processing of chocolate, aiming to enhance its sensory appeal.

Molten tribology

The friction measurements conducted on the chocolate masses revealed an intriguing phenomenon: at higher sugar loads, friction response was found to increase (Fig.4.6). This finding contradicts the typically anticipated inverse relationship between smoothness and friction (Kokini, 1987). This observed increase in friction at higher sugar levels challenges this notion, suggesting a more complex interplay between sugar content, measured friction, and perceived smoothness in chocolate.



(a) (b)

Figure 4.6: Stribeck curves of molten chocolates obtained at 35°C with a BTP geometry. (a) Pearson correlation (b) Kendall rank correlation with smoothness marked with colored background indicating positive relation in green and negative in red. Samples indicate "S" sugar conc. and "H" hazelnut oil conc. N = 3.

The correlation for each Hersey value, representing a normalized velocity point, is illustrated with a colored background area in the figure. This color-coding scheme is designed to intuitively convey the nature of the correlation: a positive correlation is indicated by a green background, while a negative correlation is shown in red. Furthermore, the intensity of the color is used to signify the level of statistical significance. A darker shade of the respective color denotes a higher level of significance of 0.01 while the lighter shade has it at 0.05.

The figures presented in the study illustrate the correlations between the friction value per velocity point and the smoothness score of the chocolate samples. Addi-

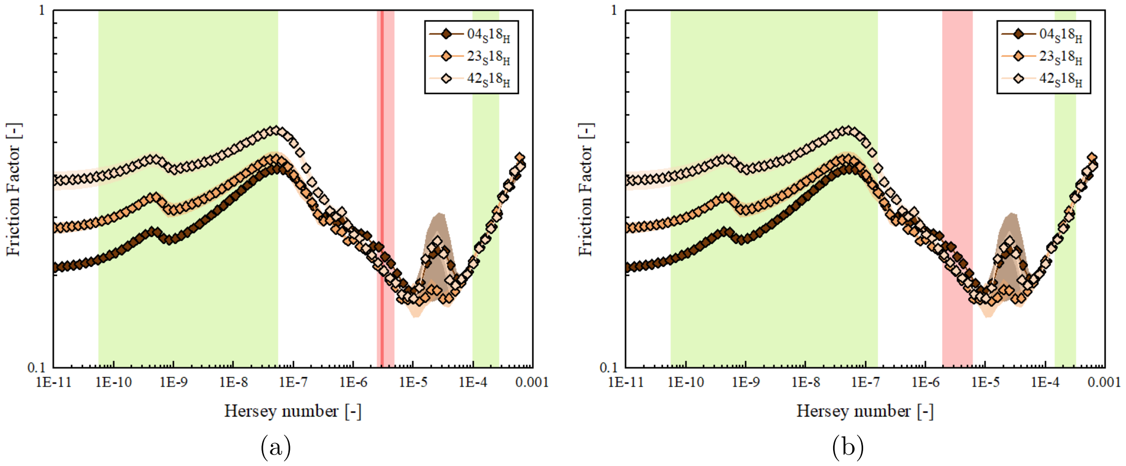


Figure 4.7: Stribeck curves of molten chocolates with added hazelnut oil obtained at 35°C with a BTP geometry. (a) Pearson correlation (b) Kendall rank correlation with smoothness marked with colored background indicating positive relation in green and negative in red. Samples indicate "S" sugar conc. and "H" hazelnut oil conc. N = 3.

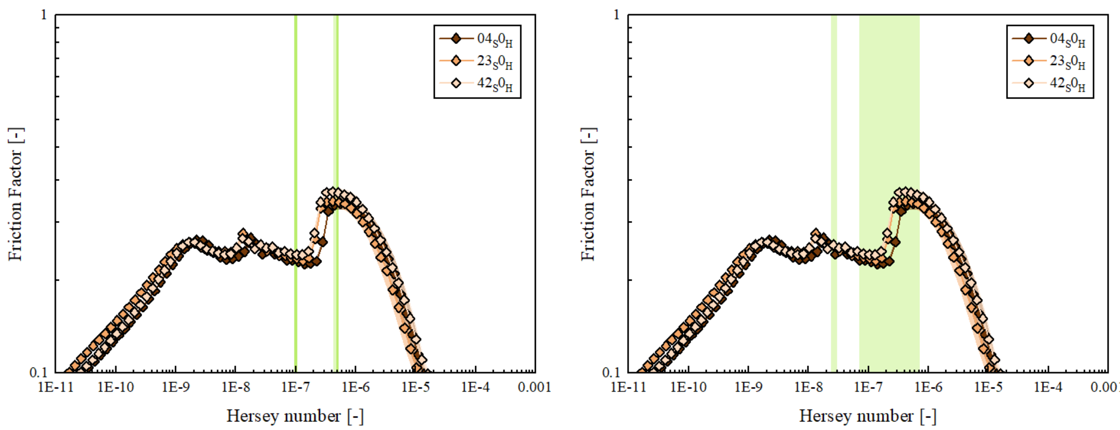
tionally, the figures include a representation of rank correlation. Unlike the standard Pearson correlation, which directly relates the measured friction values to smoothness scores, Kendall rank correlation focuses on the order of the samples. This means that instead of correlating the actual friction values, the analysis considers the relative ranking of the samples based on their friction properties and correlates this ranking with the perceived smoothness.

The anticipated inverse relationship between smoothness and friction in chocolate – where higher friction is typically perceived as less smooth – is a fundamental aspect of this study. While certain areas (indicated in red) conform to the expected inverse relationship, there are also distinct green zones that depict the opposite effect.

To delve deeper into this complex relationship, all samples, comprising different combinations of sugar and hazelnut oil (Fig.4.7), were subjected to friction analysis and correlation. This approach aimed to identify specific instances where friction measurements could be directly linked to the perception of smoothness. Notably, recurring zones of interest were identified at the end of the mixed regime of the Stribeck curves. These zones, however, were not as pronounced as the clear contradiction zones observed in the boundary lubrication zone.

Saliva tribology

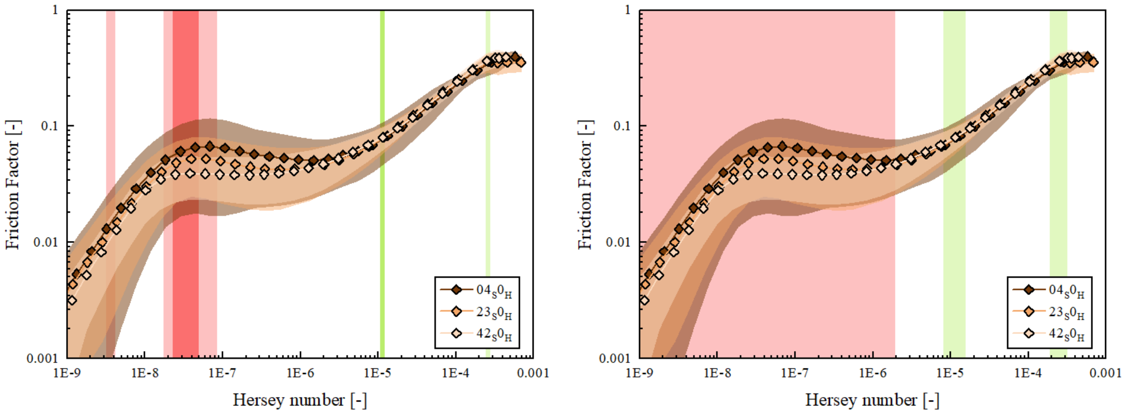
Samples were also analyzed with the addition of a saliva substitute phosphate buffered saline (PBS) solution as shown in Figure 4.8. This addition was intended to more closely mimic the actual conditions during human consumption, potentially uncovering interactions not present in the pure system. Selway and Stokes (2013a) noted that food-saliva interactions play a crucial role in determining transient lubrication properties, which may reflect dynamic oral processes. Thus being critical for understanding mouthfeel characteristics like smoothness. Interestingly, the inclusion of this saliva substitute appeared to collapse the friction response, indicating that the correlation between friction and smoothness perception becomes less pronounced in conditions that more closely resemble actual consumption.



(a) (b)

Figure 4.8: Stribeck curves of molten chocolates mixed with artifical saliva in 1:1 ratio obtained at 35°C with a BTP geometry. (a) Pearson correlation (b) Kendall rank correlation with smoothness marked with colored background indicating positive relation in green and negative in red. Samples indicate "S" sugar conc. and "H" hazelnut oil conc. N = 3.

The interaction of multiple factors can yield sensory responses that are not always predictable. The use of a saliva substitute in the analysis is a testament to the significance of simulating real-world consumption conditions in sensory studies. This approach ensures that the findings are more reflective of the actual experience of consumers.



(a) (b)

Figure 4.9: Stribeck curves of solid chocolates obtained at 35°C with the custom geometry. (a) Pearson correlation (b) Kendall rank correlation with smoothness marked with colored background indicating positive relation in green and negative in red. Samples indicate "S" sugar conc. and "H" hazelnut oil conc. N = 3.

Solid tribology

To further enhance the relevance and accuracy of the study, a custom geometry for the friction measurements was developed. This innovative setup enabled the measurement of friction responses in chocolate during its melting process, a critical aspect of the chocolate eating experience. Unlike the standard setup, which required the samples to be in a molten state throughout the measurement, this new approach offers a more realistic simulation of the conditions during sensory evaluation.

The results obtained from this improved setup showed the expected inverse trend (Fig.4.9), indicating that the method of analytical measurement plays a crucial role in understanding the relationship between physical properties and sensory perception. This finding suggests that refining and enhancing analytical techniques is essential to gain meaningful insights into how sensory data correlates with measured material properties. It underscores the need for continuous improvement in measurement methods to ensure that they can effectively capture the nuances of sensory experiences, particularly in complex food matrices like chocolate. This advancement in measurement techniques not only aids in better understanding the science behind food textures but also has potential implications for the development of products that are more aligned with consumer preferences and expectations

Observing the curves of the solid samples more closely, it becomes evident that there is room for further improvement in the experimental setup, as indicated by the relatively high standard deviation in the measurements. High standard deviation in experimental data often points to variability in the measurement process, which can stem from several factors, such as inconsistencies in sample preparation, variations in the experimental conditions, or limitations in the measurement apparatus itself.

Despite the measured material properties satisfactorily proving that the chocolate production in the pilot plant should not be basis of the observed variance, a decision was made to repeat and improve the study. This time, the scope was expanded to include chocolate samples obtained from retail, which were manufactured at an industry-grade production level.

Including industry-grade chocolate in the study also helps in assessing whether the patterns and correlations observed in the pilot plant samples hold true for commercially produced chocolates. This approach not only strengthens the validity of the research findings but also potentially uncovers new insights into the sensory and material properties of chocolate.

4.2 Commercially manufactured chocolate

For the new set of samples consisting of commercially produced chocolates, the same three sensory attributes – sweetness, bitterness, and smoothness – were evaluated again. This phase of the study involved testing five different dark chocolates with increasing cocoa content. The recipes of these chocolates revealed a consistent trend: as the cocoa content increased, there was a corresponding decrease in sugar content and a slight increase in fat content.

4.2.1 Analysis of sensory responses

The evaluation of the new set of dark chocolate samples with varying cocoa contents reaffirmed some expected trends in sensory perception, particularly regarding sweetness and bitterness, while offering nuanced insights into smoothness.

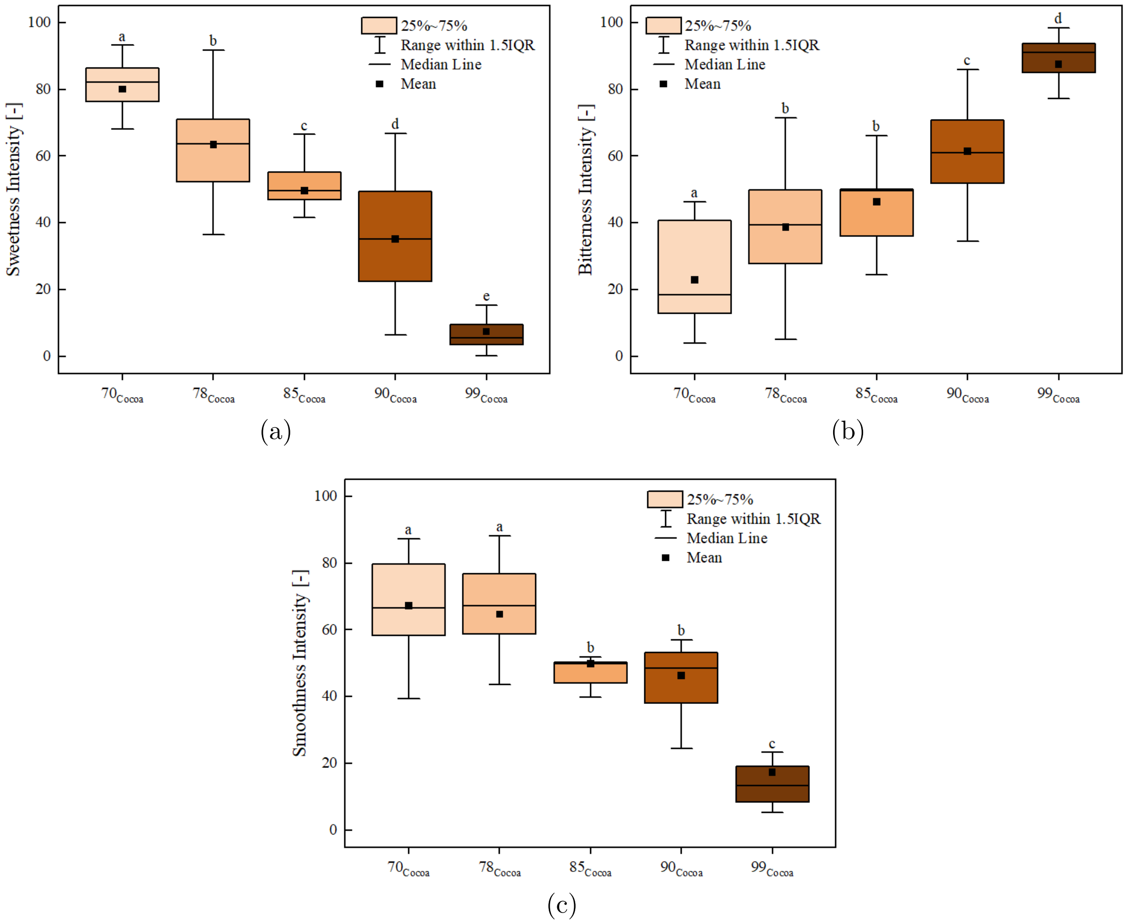


Figure 4.10: Perceived (a) sweetness (b) bitterness (c) smoothness intensity during comparative profiling (8 panellists in two sessions). Samples indicate cocoa concentration in wt%. Samples that do not share a letter are significantly different at the 0.05 level.

Sweetness

The perception of sweetness showed a clear and fully significant difference across all samples (Fig.4.10a). As the sugar content decreased in chocolates with higher cocoa content, there was a corresponding decline in the sweetness score. This direct correlation between sugar content and sweetness perception is consistent with basic principles of taste perception and previous findings.

Bitterness

For bitterness, the study observed the anticipated inverse trend relative to sweetness (Fig.4.10b). However, unlike sweetness, not all samples could be significantly distinguished based on their bitterness scores. This suggests that while increased cocoa content generally leads to heightened bitterness, the difference in bitterness between certain samples might not be perceptible enough to reach statistical significance.

Smoothness

In terms of smoothness, the results were even more varying (Fig.4.10c). The samples with lower and middle cocoa content did not exhibit significant differences in their smoothness scores, indicating a certain level of uniformity in texture perception within this range. Also Poulton (1975) describes a range effect where individuals are better at detecting differences between stimuli when those stimuli fall within a moderate range, rather than being too similar or too dissimilar. However, the study identified three distinct groups of samples that showed significant differences in smoothness. This finding implies that while some variations in cocoa content do not markedly alter the perception of smoothness, certain thresholds or specific recipe configurations can lead to noticeable changes in texture.

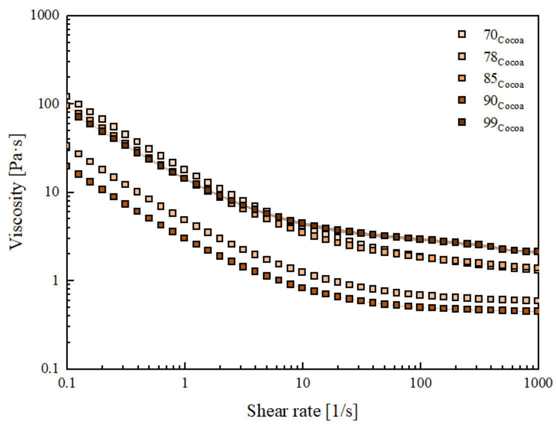
4.2.2 Characterization of physical properties

Flow behavior

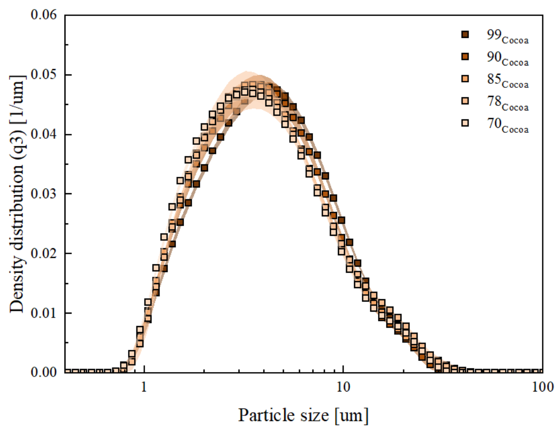
The viscosity of the commercially produced dark chocolate samples was examined, with an expectation of differences due to the variations observed in their recipes (Fig.4.11a). Indeed, the rheological analysis revealed clear distinctions between the samples across the entire shear rate range. However, these differences did not correspond to a clear trend with either cocoa content or sugar content. This lack of a straightforward relationship suggests that factors beyond just cocoa and sugar content are influencing the flow properties of these chocolates. It's possible that other recipe components (e.g. emulsifier type and content), processing conditions, or even the inherent properties of the cocoa used in these commercial samples play significant roles in determining their flow behavior.

Particle size distribution

In addition to rheological analysis, the particle size of these industry-grade chocolates was analyzed to identify any potential differences from the pilot plant samples previously studied (Fig.4.11b). The results showed that while the particle size distribution in the commercial samples was narrower, the overall size range was comparable to that observed in the first study. This finding indicates a certain level of consistency in particle size distribution between small-scale and large-scale production, despite variations in other recipe and processing parameters. This supports the hypothesis that the applied types and fractions of emulsifiers in the investigated commercial chocolates were different.



(a)



(b)

Figure 4.11: Sample characterization (a) viscosity curve at 40°C using a couette geometry. (b) particle size distribution. Samples indicate cocoa concentration in wt%. Standard deviations are colored around the mean value. N = 3.

4.2.3 Correlation of material properties and sensory attributes

The correlation analysis conducted on the commercially produced dark chocolate samples presented in Figure 4.12, mirrored the significant relationships observed in the initial study regarding the sensory attributes. Sweetness and smoothness were found to correlate positively with each other, and both showed a negative correlation with bitterness. This reaffirmation across different sets of samples strengthens the validity of these observed relationships in chocolate sensory perception.

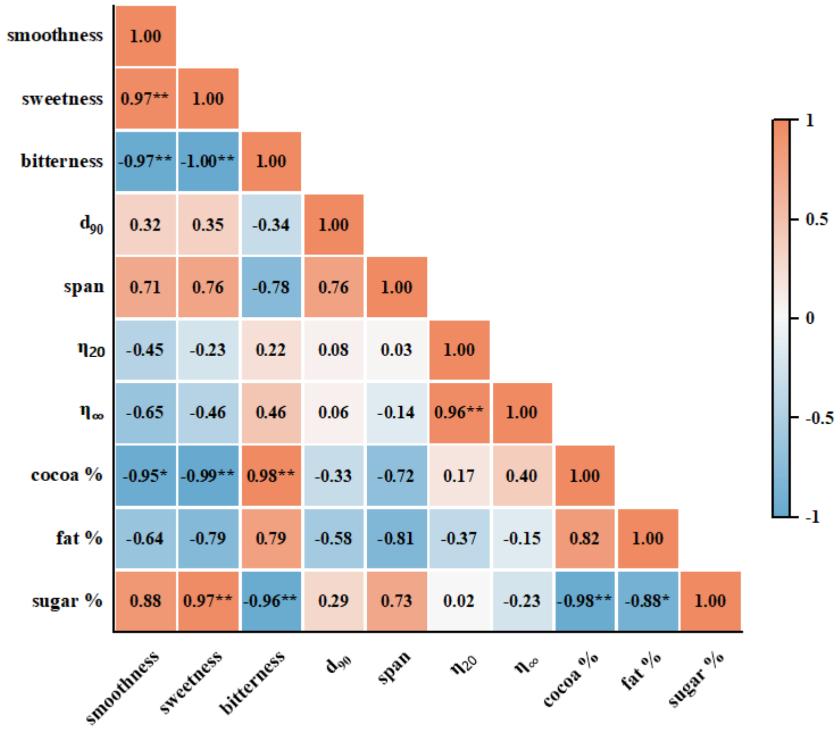


Figure 4.12: Correlation table with correlation coefficients comparing sensory evaluations to material properties. ** refers to a significance level of 0.01 and * to a significance level of 0.05.

Interestingly, the analysis indicated that smoothness was not significantly influenced by viscosity differences among the samples. This suggests that the perception of smoothness in chocolate might be governed by factors other than just these physical properties, possibly including the specific sensory characteristics of the ingredients or even the overall mouthfeel experience.

Regarding the relationship between recipe composition and sensory attributes, cocoa content was found to correlate significantly with all three sensory attributes (sweetness, bitterness, and smoothness). Ni *et al.* (2022) showed that also in their study smoothness in chocolate negatively correlated with cocoa concentration but in their study also weakly with viscosity, which was not present here. However, fat content did not exhibit such relationships. This is in contrast to other findings where fat content influences the overall texture and smoothness of chocolate products (Prindiville *et al.*, 1999). Reason could be the small range of differences in fat content compared to the rather big range of cocoa content variation in the samples.

Interestingly, sugar content did not show a significant correlation with smoothness, which could be attributed to the less pronounced differences in smoothness between these samples. Overall, these findings underscore the need for a holistic approach in understanding and optimizing chocolate formulations to cater to desired sensory profiles.

4.2.4 Analysis of friction behavior and texture perception

Molten tribology

The initial comparison of the commercial chocolate samples using the standard tribological setup revealed evident differences in the friction curves (Fig.4.13). The two chocolates (78% and 90% cocoa) which where significantly lower in their viscosities show also lower friction coefficients in the mixed friction domain and (but less pronounced) in the hydrodynamic friction domain. Interestingly in the boundry friction domain these two samples demonstrate significatly higher friction coefficients than the other samples. This could be hypothesized to be the consequence of an enhanced emulsifier interaction with the surfaces of the tribopairs.

However, a notable limitation of this method was its inability to fully correlate the variations in smoothness scores observed among the samples. This discrepancy was even more pronounced given that in the pilot plant samples, the method did, albeit in a contradicting manner, manage to capture some broad relationship between the measured friction and perceived smoothness. Despite this limitation the research already incorporated strategies to improve the experimental setup, specifically tailored to more closely represent sensory perception. These enhancements are crucial, as they aim to bridge the gap between the physical measurements obtained through tribological analysis and the actual sensory experiences of consumers.

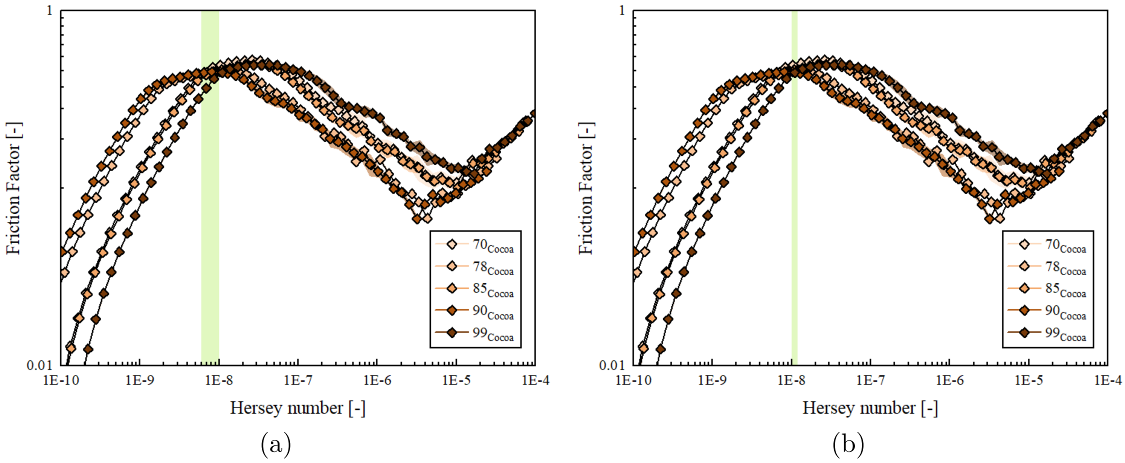


Figure 4.13: Stribeck curves of molten chocolates obtained at 35°C with a BTP geometry. (a) Pearson correlation (b) Kendall rank correlation with smoothness marked with colored background indicating positive relation in green and negative in red. Samples indicate cocoa concentration in wt%. N = 3.

Saliva tribology

The first advancement in the experimental approach involved the addition of artificial saliva to the chocolate samples shown in Figure 4.14, which were then measured in a molten state.

The artificial saliva used in this updated study was enhanced by incorporating a more complex recipe that also included mucins. This improvement is based on the recommendation made in studies by Soltanahmadi *et al.* (2023) and Sarkar *et al.* (2009). Mucins are glycoproteins found in human saliva that play a crucial role in lubrication and the overall sensory experience of food. By integrating mucins into the artificial saliva, the study takes a substantial step towards creating a more accurate simulation of the human oral environment. This enhancement is expected to provide deeper insights into how chocolate interacts with saliva during consumption, particularly regarding its textural attributes and mouthfeel.

The incorporation of artificial saliva led to a noticeable collapse in the friction curves. However, a key observation in this version of the experiment was that the collapse of the friction curves was not as pronounced as in the pilot plant samples. More importantly, this methodology revealed new regions where significant correlations to the smoothness score were evident.

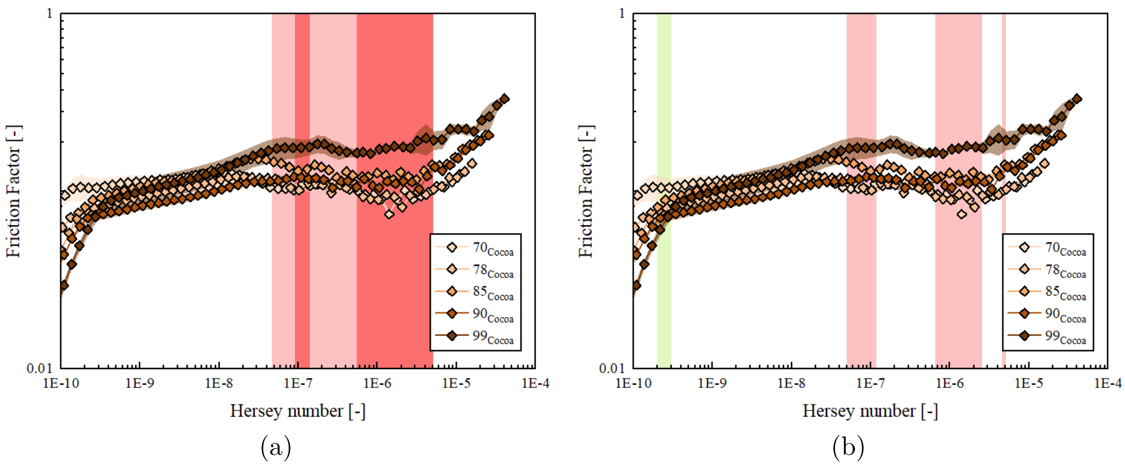


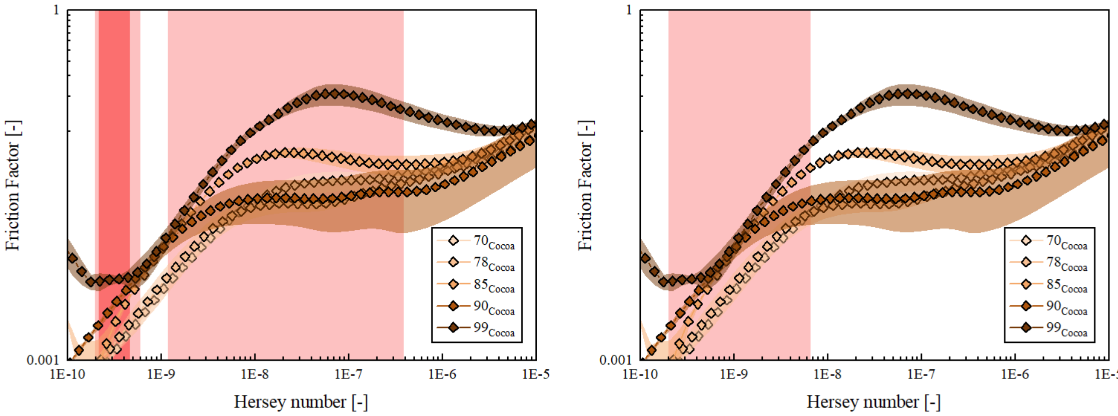
Figure 4.14: Stribeck curves of molten chocolates mixed with artifical saliva in 1:1 ratio obtained at 35°C with a BTP geometry. (a) Pearson correlation (b) Kendall rank correlation with smoothness marked with colored background indicating positive relation in green and negative in red. Samples indicate cocoa concentration in wt%. N = 3.

This finding indicates that the addition of a more complex artificial saliva, including mucins, has enhanced the sensitivity and robustness of the method. By not entirely collapsing the friction curves, the improved setup allows for the detection of subtle variations in the frictional properties of chocolate in the presence of saliva. These variations, in turn, correlate with the sensory perception of smoothness, providing a more nuanced understanding of how chocolate's textural attributes are experienced during consumption. Nevertheless, the mixing procedure of the chocolate samples with the artificial saliva has to be expected to have led to full sugar dissolution, which is not fully representative for the oral processing.

Solid tribology

The friction curves obtained using the custom solid chocolate geometry display clear and significant trends with smoothness perception, particularly in the boundary to mixed lubrication regimes (Fig.4.15). These regimes are critical in tribology as they encompass the transition from solid contact to a more fluid-dominated interaction, closely resembling the melting of chocolate in the mouth between tongue and palate.

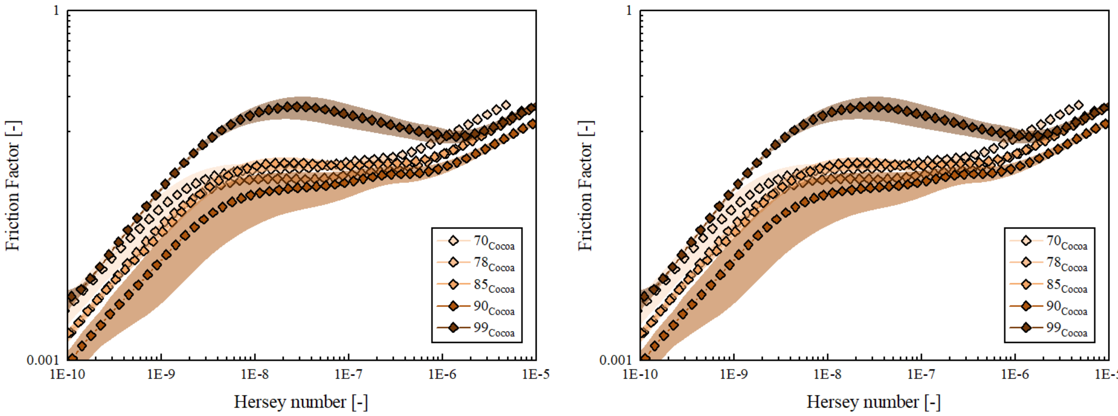
The ability of this custom setup to capture these trends is a strong indication that the approach more accurately reflects the sensory experience of chocolate consumption. By replicating the conditions under which chocolate transitions from



(a) (b)

Figure 4.15: Stribeck curves of solid chocolates obtained at 35°C with the custom geometry. (a) Pearson correlation (b) Kendall rank correlation with smoothness marked with colored background indicating positive relation in green and negative in red. Samples indicate cocoa concentration in wt%. N = 4.

a solid to a molten state during eating, the study provides a more realistic and relevant assessment of how frictional properties relate to the perceived smoothness of chocolate.



(a) added art. saliva (b) added art. saliva

Figure 4.16: Stribeck curves of solid chocolates obtained at 35°C with the custom geometry. (a) Pearson correlation (b) Kendall rank correlation with smoothness marked with colored background indicating positive relation in green and negative in red. Samples indicate cocoa concentration in wt%. Artifical saliva addition in 1:1 ratio. N = 4.

The combination of the custom solid chocolate geometry with the addition of artificial saliva in the tribological measurements yielded unexpected results, deviating from the anticipated final improvement of the methodology (Fig.4.16). Instead of presenting a refined correlation with the sensory smoothness scores, the experiments showed a collapsing effect of the saliva addition coupled with a changed friction response in solid chocolate tribology, failing to produce curves that could be significantly linked to smoothness perception at all.

This outcome underscores a crucial aspect of scientific experimentation: step-by-step improvements do not always follow a linear path of development. Several limitations and complexities emerged in these experiments, highlighting the challenges of replicating real-world consumption dynamics in a controlled analytical setting.

One such limitation is the changing ratio of saliva to liquid chocolate during the melting process in closed-lid experiments. Unlike the fully molten setup in standard tribological measurements where the two components are premixed, ensuring their interaction, the custom solid tribology setup involves applying saliva to the friction surface before introducing the solid sample. As the solid chocolate transitions to a molten state during measurement, new material is squeezed from the friction gap, potentially leading to the exclusion of the initially present saliva and negating its effect.

Moreover, the sensory testing with panelists allowed for natural movements of the chocolate samples in the mouth, including detachment of the tongue and palate, and incorporation of newly produced saliva. Such dynamic and complex movement profiles are not replicated in the analytical setup, which applies constant pressure and unidirectionally increasing sliding verlocities to the sample. These discrepancies highlight a critical gap between the experimental conditions and the actual sensory experience of consuming chocolate. And as the Hersey number has an included normalization with the flow behavior of the material, the possibly gradient value of the viscosity in the gap cannot reflect a fully correct placement of the measurement points onto the stribeck curve.

These findings illuminate the need for further refinement and innovation in the experimental design to more accurately capture the complexities of chocolate consumption. It may involve developing methods that allow for more dynamic interactions between saliva and chocolate or adjusting the pressure and movement profiles to better mimic natural consumption patterns. The study exemplifies the iterative nature of scientific research, where each experiment, regardless of its outcome, contributes valuable insights that guide subsequent advancements.

4.3 Tongue topography enhanced perception

During the extensive sensory studies presented in more detail in chapter 6, images of tongue surfaces of 49 panelists were collected. This data allowed for the extraction of key values describing the topography of the human tongue, focusing particularly on two types of papillae - fungiform and filiform. The fungiform papillae are linked to sweetness perception. Liao and Schultz (2003) found that fungiform papillae contain taste receptor cells for sweet flavors, as indicated by the expression of sweet receptor genes. Filiform papillae, are known for their role in texture perception due to their deformation during consumption. Lauga *et al.* (2016) suggested that filiform papillae may act as direct strain sensors or indirect strain amplifiers for the underlying mucosal tissue in the tongue.

The tribological measurements till now in this study were conducted using surfaces that aimed to mimic the interaction between the human tongue and palate. These surfaces, while using materials typical in soft tribology, had a flat structure for all the results presented previously. However, the study of the tongue surfaces revealed a distinct contrast between these flat surfaces and the intricate microstructure found on a real human tongue. Moreover, it was observed that the sizes and distribution of these microstructures are not uniform across the entire tongue surface, with different zones exhibiting varying ratios of these structures.

Ranc *et al.* (2006) investigated how different surface structures affect friction and lubrication properties in a theoretical surface model representing tongue/palate contact. And in a more recent publication Andablo-Reyes *et al.* (2020) also delved into developing biomimetic surfaces that replicate the topography of the human tongue.

In response to these findings, the study took an additional step by selecting three regions on the tongue, each characterized by their average microstructure for later comparison. Based on these characterizations, new tribosurfaces were fabricated to mimic the specific conditions of these tongue regions. The selection of regions was influenced by the finding of Wang *et al.* (2019) where they studied the effect of different tongue surface area topographies and their effect on friction analysis.

By incorporating tribosurfaces that replicate the actual microstructures of the human tongue, the study aims to gain a more accurate understanding of the interaction between these structures and food products, especially in terms of texture perception. This methodological enhancement is expected to provide deeper insights into the complex dynamics of food consumption and sensory perception, bridging the gap between controlled laboratory measurements and the real-world eating experience.

4.3.1 Analysis of sensory responses

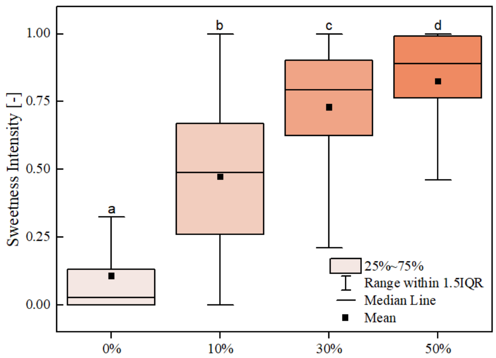


Figure 4.17: Perceived sweetness intensity during comparative profiling (49 panellists in one session). Samples indicate sugar concentration in wt%. Samples that do not share a letter are significantly different at the 0.05 level.

In Figure 4.17 the sensory studies conducted with simple sugar solutions of varying concentrations provided straightforward results: a clear and significant trend showing higher sweetness scores with increasing sugar content. This finding aligns with the basic principles of taste perception, where higher concentrations of a taste substance typically lead to stronger sensory responses. However, the study took a more nuanced approach by correlating these sensory results with the individual tongue surface structures of the panelists, along with other varying factors collected during the experiment. This approach represents a sophisticated attempt to understand the interplay between the physiological characteristics of the panelists and their sensory experiences.

4.3.2 Characterization of tongue topographies

For context and reference, characterizing values of the three tongue areas under study are presented in Table 4.1. These areas are chosen based on their relevance to the study's objectives — likely including zones rich in fungiform and filiform papillae, given their roles in taste and texture perception.

Table 4.1: List of characterizing values of the three tongue topography segments used for correlation and applied to the biomimetic tongue emulating surfaces used in tribological measurements.

segment	fungi num density	fungi radius	fili density
Tip	23.12	423.34	0.36
C1	40.40	314.19	0.34
C2	12.01	313.23	0.63

4.3.3 Correlation of tongue topographies and sensory attributes

Interestingly, when the sweetness ratings were correlated with the panelists' tongue surface structures, no clear overall trend emerged between the sensory assessment and the microstructure of the tongue. The only significant correlation was observed when the slope of the fit was related to the average size of the fungiform papillae at the tongue apex. Given that fungiform papillae are directly linked to sweetness perception, this correlation was not entirely unexpected. However, it was somewhat surprising that more correlations between sweetness perception and the distribution of fungiform papillae were not found, given their known role in taste sensation. This outcome highlights the complexity of taste perception and the challenges in directly linking physiological factors, such as tongue microstructure, to sensory experiences.

The full discussion of the correlation matrix seen in Figure 4.18 and the interaction of the other panelist factors with sweetness perception was saved for a later chapter (see 7.1) and allows for a more focused examination in this subchapter on the specific interaction between tongue surfaces and tribological friction measurements.

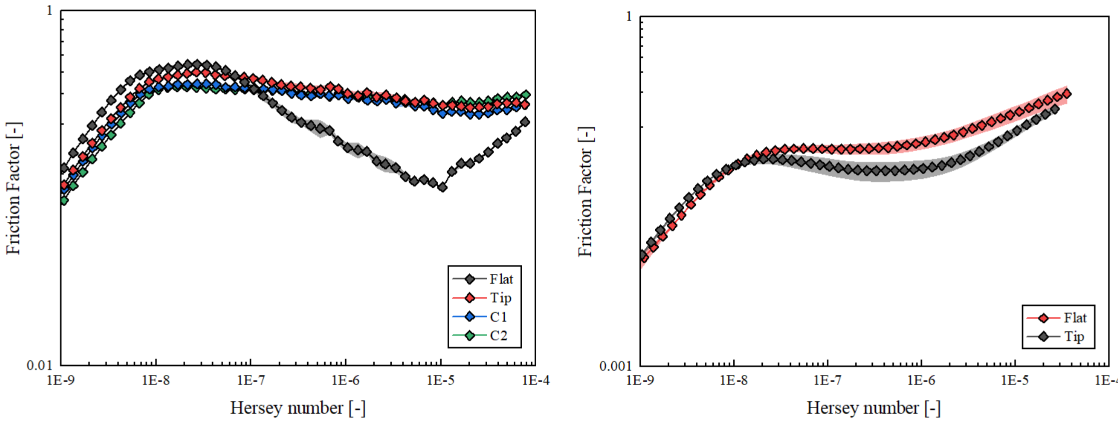
Figure 4.18: Correlation table with correlation coefficients comparing sensory evaluations and panelist characteristics to tongue topography properties. ** refers to a significance level of 0.01 and * to a significance level of 0.05.

4.3.4 Analysis of friction behavior and texture perception

The middle sample 85_{cocoa} was chosen as a reference point to illustrate the effect of different surface structures on tribological measurements as shown in Figure 4.19. By presenting the results of this particular sample under varying conditions—both in its molten and solid states—while subjected to tribological testing with different simulated tongue surfaces, the study offers a comprehensive overview of the impact of surface microstructure on frictional properties.

The presence of microstructuring on the surface led to a flattening of the friction response curve. This observation suggests that the intricate topography of the tongue's surface can significantly influence the frictional characteristics of food during consumption. Interestingly, no clear trend emerged when comparing different microstructured surfaces, as all variations converged onto a single trend, differing markedly from the response observed with the flat surface.

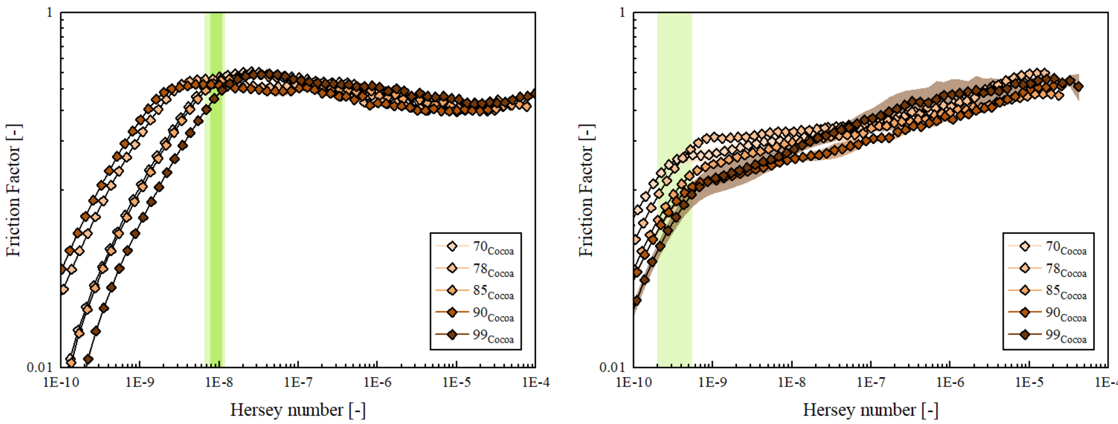
In the solid state experiments, the study focused on two surfaces: the flat standard and the surface mimicking the microstructure present at the tip of the tongue. The



(a) (b)

Figure 4.19: Stribeck curves of (a) molten (b) solid chocolates without saliva obtained at 35°C with (a) BTP (b) custom geometry. Samples indicate surface topography. N = 3.

findings from these experiments further emphasize the changing influence of surface structure on friction measurements.

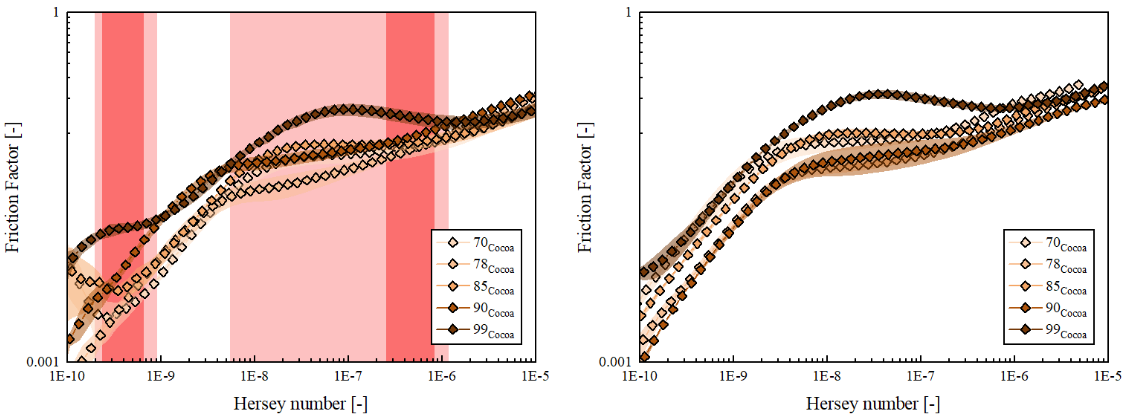


(a) (b) added art. saliva

Figure 4.20: Stribeck curves of molten chocolates using structured tribosurfaces based on segment 'Tip' obtained at 35°C with a BTP geometry. (a) without artifical saliva (b) with artifical saliva addition in 1:1 ratio. Correlation with smoothness marked with colored background indicating positive relation in green and negative in red. Samples indicate cocoa concentration in wt%. N = 3.

The investigation into the impact of the surface structure at the tongue tip on friction measurements, both in molten shown in Figure 4.20 and solid states in Figure 4.21, yielded mixed results in terms of correlation with smoothness perception. While these experiments did not reveal any new improvements in correlating friction measurements to perceived smoothness, they offered some crucial insights.

A key observation was that the incorporation of microstructuring, especially in the most advanced setup with the custom geometry, did not diminish the correlation power with the smoothness score. This suggests that the microstructure of the tongue surface, as replicated in the tribological setup, does not interfere with the ability to capture the sensory perception of smoothness. It maintains, if not enhances, the relevance of the friction measurements to real-world sensory experiences.



(a) (b) added art. saliva

Figure 4.21: Stribeck curves of solid chocolates using structured tribosurfaces based on segment 'Tip' obtained at 35°C with the custom geometry. (a) without artifical saliva (b) with artifical saliva addition in 1:1 ratio. Correlation with smoothness marked with colored background indicating positive relation in green and negative in red. Samples indicate cocoa concentration in wt%. N = 4.

The solid experiments (Fig. 4.21) without the addition of artificial saliva still demonstrated a clear and broad trend in the mixed lubrication regime. This trend aligns well with the panelists' perception of smoothness, indicating that even without the saliva component, the tribological measurements are capable of reflecting sensory experiences to a considerable extent.

Even if the findings do not fully validate the importance of including tongue-like microstructures in tribological setups to improve correlation with sensory perception, improving the method to mimic human sensory conditions more accurately is still regarded as going into the right direction. The study's approach, by methodically evaluating the impact of various experimental modifications, underscores the intricate interplay between physical measurements and sensory perception, guiding future research and methodology enhancements in the field of food tribology and sensory analysis.

5 Taste and aroma percepetion of surface structured chocolate

Transitioning to the next chapter, the focus shifts to how the structuring of chocolate surfaces, infused with different levels of sweetness agents and foamed materials, can impact sensory perception. The structuring of sample surfaces in this context refers to the deliberate modification or engineering of the surface topography of the food samples. This could involve creating patterns of differing tastant loads or varying the surface area that comes into contact with the taste receptors or olfactory senses. The use of different levels of sweetness agents and the incorporation of foamed materials, which can alter texture, are having significant effects on how these samples are perceived in terms of sweetness and aroma.

By examining the interaction between surface structure and sensory experience, the research explores an area that is of high impact for food design and innovation. The findings from this chapter could have practical applications in the development of new food products, particularly those where texture and flavor perception are key to consumer satisfaction and preference.

The first part of this chapter discussing thaumatin enhanced surface structures was published together with the following authors and contributors (Burkard, Kohler, et al., 2023):

- Johannes Burkard: conceptualization, methodology, supervision, data curation, validation, visualization, writing
- Tanja Berger: data curation, formal analysis, investigation
- Mitsuko Logean: data curation, formal analysis, investigation
- Kim Mishra: investigation, validation, writing
- Erich Windhab: data curation, validation, funding acquisition
- Christoph Denkel: data curation, validation, funding acquisition, writing
- Lucas Kohler: conceptualization, methodology, supervision, data curation, validation, visualization, writing

5.1 Thaumatin enhanced surface structures

In this study sweetener was placed on sample surfaces influences the sensory perception of sweetness in chocolate. It was imperative to first rule out any effects that could arise from factors other than the tastant concentration. Especially possible differences in texture between the samples that could influence other percpetion aspects. Brossard *et al.* (2006) reported that sweetness intensity varied with the texture in dairy desserts, likely due to physicochemical interactions. This necessitated the clear characterization of the chocolate surface masses texture properties.

5.1.1 Characterization of physical properties

Flow behavior

The study consistently observed shear thinning behavior across all samples as seen in Figure 5.1a, typical for chocolate masses (Glicerina *et al.*, 2013). This uniformity in flow behavior across the samples was critical in ensuring that any perceived differences in sweetness were not influenced by variations in the textural properties of the surface mass.

Melting behavior

Additionally, all samples exhibited a single melting peak within a temperature range of 33-35 °C (Fig.5.1b). The presence of a distinct melting peak within this range resembles that of well-tempered chocolate Van Malssen *et al.* (1996), which is known for its desirable texture and mouthfeel. The consistency in melting behavior across the different sweetener concentrations further supported the hypothesis that textural variations were minimal.

This negligible variance in both melting and flow properties among the chocolate surface masses with varying sweetener concentrations led to an important conclusion: the sensory perception of sweetness in these samples was likely to be influenced predominantly by the concentration of the tastant itself, rather than by any textural differences. This finding was crucial as it validated the primary focus of the study, which was to isolate and understand the direct impact of sweetener concentration and its distribution on sweetness perception, without the confounding effects of textural variations.

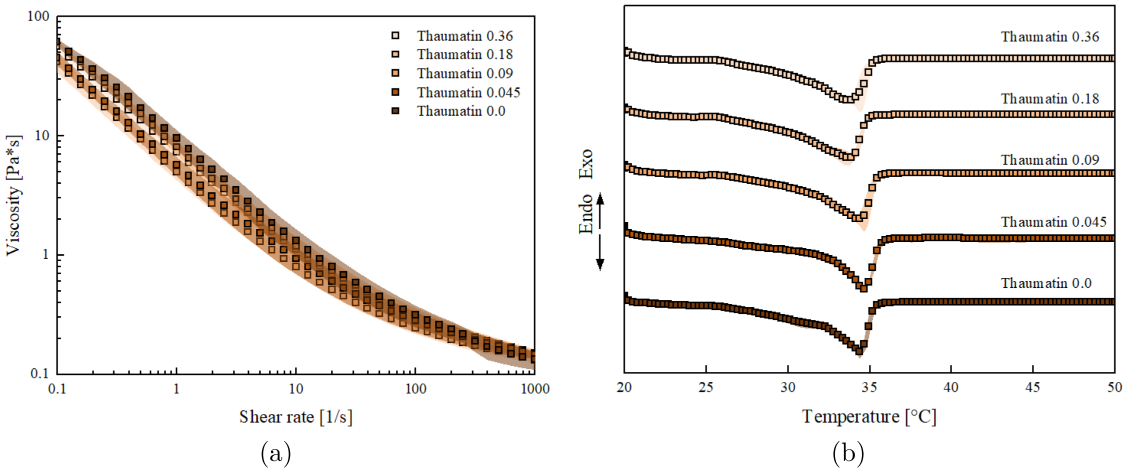


Figure 5.1: Sample characterization (a) viscosity curve at 40°C using a couette geometry. (b) DSC curves. Samples indicate thaumatin concentration. Standard deviations are colored around the mean value. N = 3.

5.1.2 Analysis of sensory responses

Time-dependent sensory analysis was conducted to observe sweetness perception at three distinct time points: "tstart," "tmax," and "tend." This approach aimed to determine whether the impact of sweetener placement was dominant at a specific time during consumption or sustained throughout the entire duration.

Evenly distributed surface patterns

The study compared various samples with different surface patterns to a reference sample named "Bulk," which represented a standard chocolate with evenly distributed sweetener, but without any sweetened surface modification. This comparison shown in Figure 5.2, revealed an interesting finding regarding surface structuring. The patterned samples exhibited a pronounced increase in sweetness perception, with the increase reaching as high as 300% compared to the Bulk sample. This significant enhancement in sweetness emphasises the potential of strategically positioning the sweetener on the surface of the chocolate, bringing it into closer proximity to the taste receptors, as opposed to having it dispersed throughout the bulk of the chocolate (Hollowood *et al.*, 2008). The distribution within the Bulk sample likely led to a slower release rate of the tastant during oral processing. Similar effects of structure influencing release kinetics and perception were already recorded by Holm (2006) and Moskowitz and Arabie (1970).

Among the samples with different surface patterns, no significant variance was observed in sweetness perception. Since the total sweetener concentration was constant across all samples, this result suggests that the specific pattern of the surface does not significantly impact the perception of sweetness. The overall placement of the sweetener onto the surface itself plays a more critical role compared to an evenly distributed sample.

What was particularly surprising was the persistence of the enhanced sweetness perception until the end of consumption. This continued even after the surface structure had melted and the unsweetened chocolate base became more dominant in replacing tastants at the receptor level. Although there was a decrease in the sweetness boost over time, the patterned samples consistently outperformed the Bulk sample in terms of sweetness perception. This observation implies that the renewal of sweetener at the receptors is not a rapid or dominant factor. Instead, the initial effects experienced at the beginning of consumption have a lasting impact, not entirely diminished by the introduction of new molten bulk material during eating. This finding highlights the dynamics of tastant release and perception, suggesting a more complex interplay between initial tastant exposure and ongoing sensory experience during chocolate consumption.

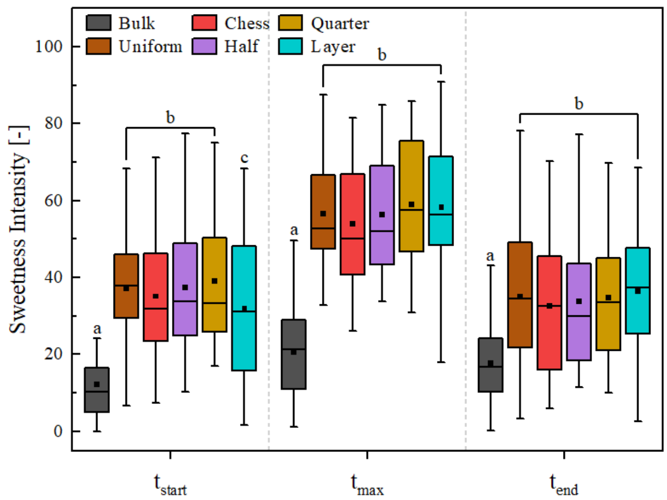


Figure 5.2: Perceived sweetness intensity during comparative profiling (17 panellists in two session) at three time points. Different surface patterns are indicated. Samples that do not share a letter are significantly different at the 0.05 level.

Unevenly distributed surface patterns

The initial study involved patterns that uniformly distributed the sweetener across the surface area. The second study introduced two new patterns to explore the impact of localized sweetener placement: one with a "Center" pattern, where the sweetener was concentrated in the middle of the sample, and another named "Periphery," where the sweetener was placed at the ends of the sample. This design aimed to create a scenario where different areas of the tongue encountered varying concentrations of sweetener, engaging different tongue zones to varying degrees. Despite these changes in pattern, the overall concentration of sweetener in each sample remained constant.

Consistent with the findings of the previous study, the patterned samples in this second study presented in Figure 5.3, demonstrated an increased sweetness perception compared to the Bulk sample. This reinforces the notion that the placement of sweetener on the surface significantly influences sweetness perception.

However, a notable difference emerged between the new pattern samples. The "Center" pattern, with the sweetener concentrated only in the middle, resulted in a decreased overall perception of sweetness compared to the uniformly distributed pattern and the "Periphery" pattern. This suggests that the sweetener in the "Center" sample may not have effectively reached a broad area of the tongue surface, possibly engaging fewer sweetness receptors. In a previous study increased taste perception at the tip of the tongue was reported by Collings (1974). Suggesting the "Center" sample did not cover the tip area.

In contrast, both the uniform sample and the "Periphery" sample appeared to cover a larger area of the tongue, potentially reaching more receptors. Intriguingly, despite the differing placement of sweetener, the "Periphery" sample's sweetness perception was not significantly different from that of the uniform sample. This indicates that concentrating the sweetener at the ends of the sample did not further enhance the perception of sweetness but rather elicited a sensory response comparable to the evenly distributed pattern.

These findings highlight the complexity of tastant distribution and its interaction with the tongue's surface in determining sensory perception. The study illustrates that not only the amount of sweetener but also its spatial distribution plays a crucial role in how sweetness is perceived. This has significant implications for food design, suggesting that strategic placement of tastants can be as important as their concentration in enhancing sensory experiences.

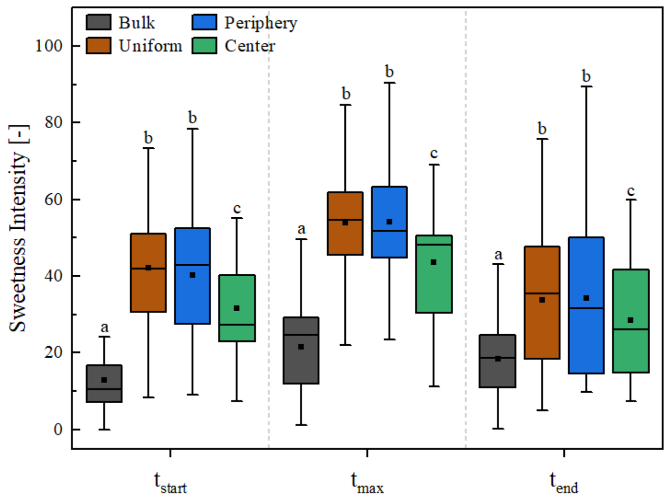


Figure 5.3: Perceived sweetness intensity during comparative profiling (17 panellists in one session) at three time points. Different surface patterns are indicated. Samples that do not share a letter are significantly different at the 0.05 level.

The results from these studies suggest that the enhanced sweetness perception is primarily driven by the initial contact between the tongue and the sweetened surface, accompanied by an increased release of tastant upon this contact. This insight led to a further investigation focusing on the first contact effects and how they contribute to the overall sensory experience.

5.1.3 Investigation of surface contact area effects

To better understand these initial contact dynamics, the study linked the initial tongue-sample contact area to the sweetener concentration, thereby defining an initial stimulus size. This approach allowed for a quantification of the initial exposure of the tongue to the sweetener.

The structural design of the patterns, consisting of dots on the surface, presented an opportunity to explore the effect of covered area on sweetness perception. The patterns created a slight 3D surface structure, and the study compared the base area of these dots with their theoretical half-sphere surface area. Given the practicalities of printing these patterns, it was assumed that the actual surface area of the dots would range between these two extremes.

Graphs included in this section of the study also encompassed data from training sessions where the overall concentration of the sweetener in the samples was varied.

By correlating the sweetness perception against this defined stimulus size, a linear relationship was revealed (Fig.5.4). This linearity suggests that the initial contact area, and consequently the initial exposure to the sweetener, plays a significant role in determining the intensity of sweetness perception.

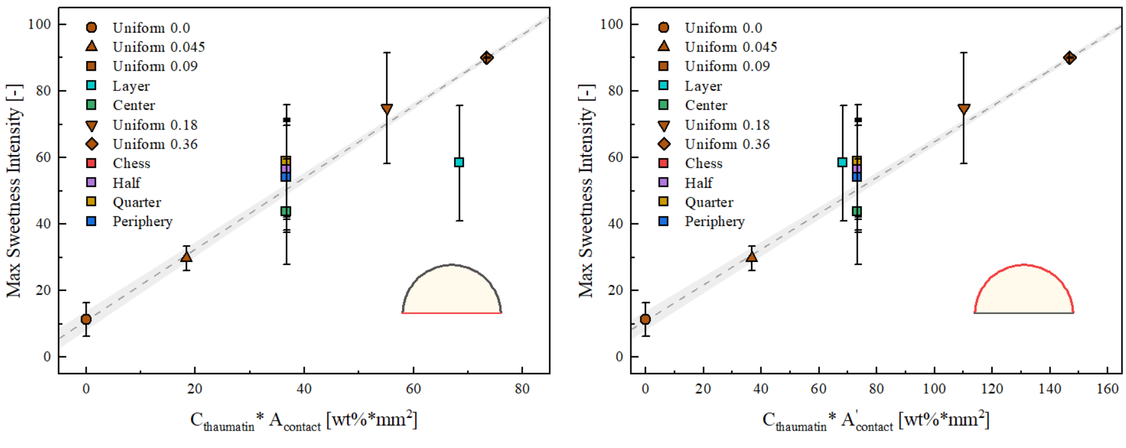


Figure 5.4: Maximum sweetness intensity as a function of initial stimulus size (17 panellists) $R^2 = 0.99$. Representative contact area is visualized.

The study's exploration of sweetness perception extended to include a "Layer" sample, which featured an even coverage of the sweetener mass across the entire surface. This addition provided a useful contrast to the dotted patterns and helped in understanding the role of contact area coverage in taste perception.

In the analysis, two approaches were used to represent the contact area: one based on the base area of the dots and the other corrected for the half-sphere surface area of perfectly round dots. When the base area of the dots was used, the Layer sample showed a notably reduced perceived sweetness in the graph. However, when the analysis was adjusted to account for the half-sphere surface area, the Layer sample aligned with the linear relationship between stimulus size and sweetness perception observed in other samples.

Further examination of the Layer sample as emphasized in Figure 5.5, revealed that the sweetness perception at all three time points ("tstart," "tmax," and "tend") was not significantly different. This observation suggests that the representation of stimulus size using the half-sphere surface area of the dots is more reflective of the actual sensory experience. It implies that the tongue's elasticity allows it to

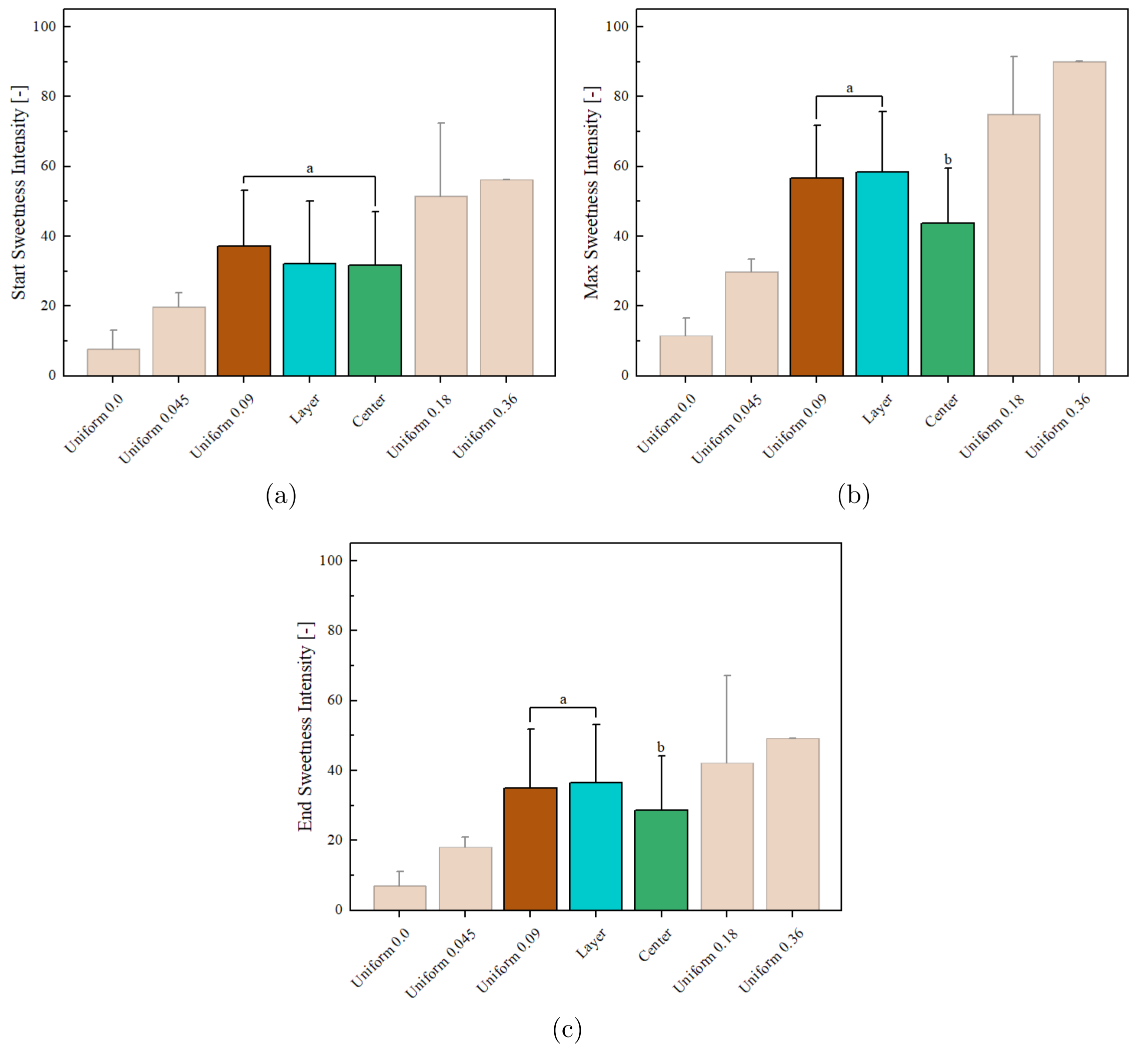


Figure 5.5: Perceived sweetness intensity during comparative profiling (17 panellists in one session) at (a) t_{start} (b) t_{max} (c) t_{end}. Different surface patterns are indicated. Samples that do not share a letter are significantly different at the 0.05 level.

conform to the 3D surface structure of the dots upon initial contact, effectively engaging with the entire surface area of each dot.

These findings underscore the complexity of the relationship between the physical structure of food surfaces and sensory perception. They suggest that the tongue's ability to adapt to surface topographies plays a critical role in how taste stimuli are perceived.

5.2 Microfoamed surface structures

In the final part of the surface study, attention was turned to examining the impact of microstructure of the surface masses, particularly with varying levels of air inclusion, on both aroma and sweetness perception. Bikos *et al.* (2022) showed that air inclusion in chocolate can trigger significant differences in sensory percpetion.

The method involved adjusting the amount of air incorporated into the foam masses, which were then used to create the surface of the samples. The aroma was infused into these foam masses and uniformly applied across the surface of each sample. Notably, the absolute content of the aroma in each sample was kept constant, ensuring that any perceived differences could be attributed solely to the changes in the amount of incorporated air. It's important to note that these samples did not have any variation in sugar or sweetener content, further isolating the impact of air incorporation on sweetness perception.

The hypothesis driving this study was that the altered texture, due to different levels of air incorporation, would facilitate the release of the aroma from the matrix. Volatile aroma components may be trapped in the air inclusions and thus the release during consumption may be facilitated giving a boost to aroma perception. As reference the bulk sample incorporated the aroma in the chocolate mass.

5.2.1 Analysis of sensory responses

In terms of methodology, the study employed a two-alternative forced choice approach where samples were evaluated in pairs. The sensory panel was instructed to choose the sample that they perceived to have a higher level of aroma or sweetness intensity.

Sweetness

The observations regarding sweetness perception in Figure 5.6 with air-incorporated samples revealed some intriguing trends. As the air content in the samples increased, there was a trend towards a higher proportion of panelists choosing these samples as sweeter. However, this trend was not statistically significant, indicating that the increase in air content did not lead to a notable enhancement in perceived sweetness.

The sample with no air inclusion, when compared to the bulk sample, even displayed a reduced sweetness perception. This finding diverges from previous observations where surface structuring generally led to an enhanced perception compared to the

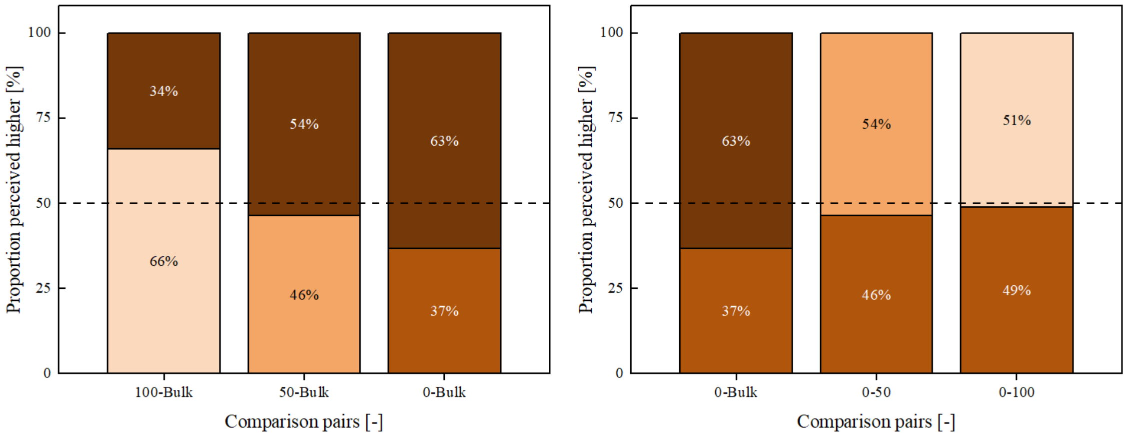


Figure 5.6: 2AFC results of sweetness evaluation (22 panellists in two session) with proportion of choice value. Comparison pairs are indicated.

bulk sample. In this case, it appears that merely placing the tastant on the surface, without any air inclusion, might have an inhibiting effect on sweetness perception.

When the surface-structured sample without air was used as a reference point, there were also no significant differences in perceived sweetness between the various samples.

Hazelnut aroma

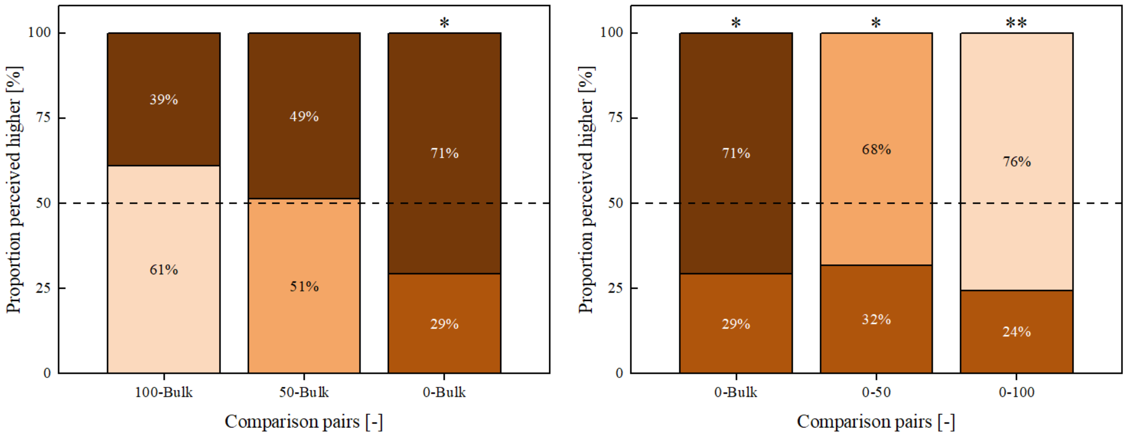


Figure 5.7: 2AFC results of aroma evaluation (22 panellists in two sessions) with proportion of choice value. Comparison pairs are indicated. Significant differences at the 0.05 level are marked with *, 0.01 with **.

Figure 5.7 highlighting aroma perception in the context of surface structuring with varying levels of air inclusion yielded distinct and significant results, demonstrating the effects of structural modifications on sensory experiences. A growing trend was observed, where samples with higher air inclusion were increasingly selected by panelists as having stronger aroma perception. This trend matches the observations in sweetness perception, where the impact of air inclusion was also increasing perception.

Notably, the study found a significant inhibiting effect on aroma perception in the sample without air inclusion compared to the bulk sample. This finding is particularly significant as it provides evidence that surface structuring, in the absence of air inclusion, hinders the perception of aroma. One possible explanation for this inhibition is that the denser, non-porous surface mass might not release the aroma effectively enough, leading to it being overpowered or flushed away by the non-surface mass of the chocolate. Consequently, the aroma might be swallowed before it has the chance to fully develop its retronasal effect, which is crucial for the perception of aroma.

When comparing the no-air-inclusion sample to other samples, it was found that all other samples were significantly perceived as having a stronger aroma. This suggests that the presence of air inclusion in the surface mass plays a critical role in enhancing aroma perception.

In conclusion, the study sheds light on the complex role of surface structuring in sensory perception. While surface structuring alone can inhibit the perception of aroma, the introduction of air into these structured surfaces can counteract this effect, and enhance aroma perception again. This insight is particularly valuable in the field of food design, where understanding the balance between texture and sensory perception can guide the development of products that deliver a more satisfying and intense sensory experience. The findings highlight the potential of using structural modifications, such as air incorporation, as a tool to manipulate and enhance the sensory attributes of food products.

6 Neuroscientific approaches in sensory science

This chapter deepens the exploration into the topic of sensory perception, particularly focusing on how gustatory stimuli trigger physiological and neurological responses.

Investigating how different concentrations of sweet and bitter tastants, as well as their textural variations introduced by xanthan gum, influence sensory experience. This is achieved by correlating sensory evaluations with physiological reactions, as measured by changes in pupil size, and neurological responses, as indicated by Event-Related Potentials (ERPs). The study meticulously observes how these physiological and neurological markers vary in response to changes in taste intensity, hedonic value, and the presence of textural modifiers.

A unique aspect of the study involves examining the impact of the rating task itself on the physiological and neurological responses. By comparing trials with and without a subsequent rating step, the study assesses whether the anticipation of providing a rating influences the sensory processing mechanisms, as reflected in pupil dilation and brain activity.

6.1 Sweetness percpetion under different consumption protocols

Participants were asked to evaluate sugar solutions of four different concentrations and assign a sweetness score to each. A key aspect of the study was examining the influence of the consumption protocol on sweetness perception, particularly focusing on the role of tongue movement. In their study Green and Nachtigal (2012) found that tongue movement could enhances the savory taste of monosodium glutamate.

Participants were subjected to two different conditions during the sensory testing: in half of the trials, they were allowed to move their tongue freely, while in the other half, they were instructed to keep their tongue still and refrain from any movement. This experimental design was crafted to investigate whether the physical act of moving the tongue, which is a natural part of the eating process, influences the perception of sweetness and is associated with distinct brain activity patterns.

6.1.1 Analysis of sensory responses

The sensory analysis presented in Figure 6.1, yielded significant differences in sweetness perception between the samples with varying sugar concentrations, confirming the expected correlation between sugar concentration and perceived sweetness (Johnson and Clydesdale, 1982). However, the impact of the consumption protocol – specifically the restriction of tongue movement – revealed nuanced findings. Significant differences in perception were only observed in the samples with higher sugar concentrations. This suggests that the physical interaction of the tongue with the sample, particularly for more concentrated solutions, might play a role in how sweetness is perceived.

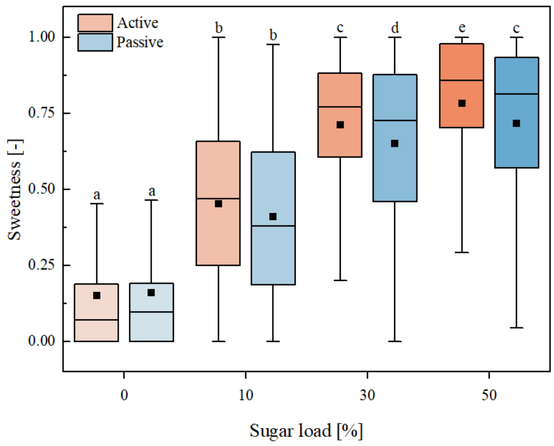


Figure 6.1: Perceived sweetness intensity during comparative profiling (49 panellists in one sessions). Consumption protocol is indicated. Samples indicate sugar concentration in wt%. Samples that do not share a letter are significantly different at the 0.05 level.

6.1.2 Analysis of pupil dilation

Focusing on pupil dilation response to gustatory stimuli, recordings were made over a 5-second period following the administration of the taste samples. The testing setup was designed to minimize potential distractions, ensuring that the recorded pupil responses were primarily influenced by the properties of the sample and possibly the participants' decision-making processes. The sweetness rating of the samples was conducted after this 5-second observation period. Pupil dilation caused by a gustatory taste stimuli were already reported by Hess and Polt (1966).

Sensory rating correlation

The pupil dilation curves observed in Figure 6.2 exhibited a consistent pattern across the different samples. Upon receiving the sample, the participants' pupils dilated, followed by a longer phase where the pupils gradually returned to their normal size. This pattern of initial dilation and subsequent relaxation is indicative of the physiological response to sensory stimulation.

The graphs illustrating these findings include distinct shaded areas to highlight zones of statistical significance in the data. The presence of two shades – a lighter and a darker one – represented different levels of statistical significance. The lighter shade corresponded to a significance level of 0.05, while the darker shade indicated a stronger significance level of 0.01. These marked areas on the graph served to pinpoint the moments when the pupil responses were significantly correlated with the sweetness ratings provided by the participants.

The significance of these correlations is noteworthy as it underscores the potential of using pupil dilation as a physiological marker for sensory evaluation. This approach provides an objective measure to complement subjective sensory assessments, offering a more holistic view of how individuals experience and respond to taste stimuli.

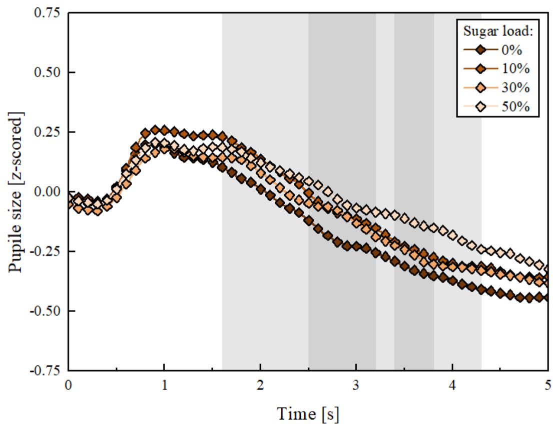


Figure 6.2: Mean pupil size curves of different sugar concentration samples (49 panellists in one sessions). Correlation modelled as a LME with sweetness rating marked with shaded background indicating significance at level of 0.05 and darker shade at 0.01.

Sugar concentration correlation

In addition to correlating pupil dilation with sensory evaluation values, the study also explored whether the specific properties of the tested sample, particularly the sugar concentration, could be predicted based on the pupil size recordings (Fig.6.3). This analysis aimed to establish a direct link between the objective physiological response (pupil dilation) and the quantifiable attribute of the sample (sugar concentration).

Not surprisingly, given the previous findings, this prediction yielded significant areas similar to those observed in the correlation with sensory ratings. Since the sensory ratings had already demonstrated a link to the material properties of the samples, this outcome was somewhat anticipated.

However, the significance of this finding lies in its validation that the physiological response, as measured by pupil dilation, can indeed be correlated with specific properties of food samples, such as sugar concentration. The graph presented in the study serves as empirical evidence supporting this correlation, illustrating that known concentrations of a tastant in a sample can be associated with the test person's eye response.

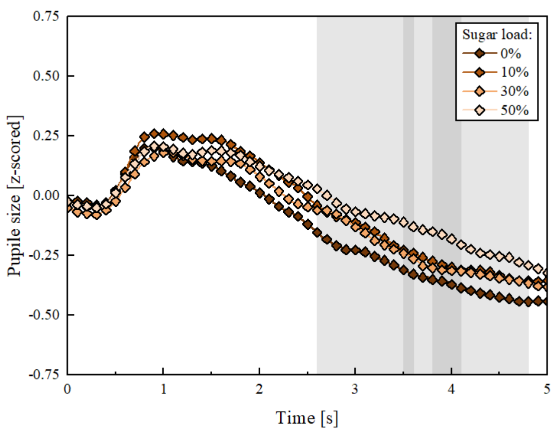


Figure 6.3: Mean pupil size curves of different sugar concentration samples (49 panellists in one sessions). Correlation modelled as a LME with sugar concentration marked with shaded background indicating significance at level of 0.05 and darker shade at 0.01.

Figure 6.4 is used to illustrate the correlation between pupil sizes and sugar concentrations, treating the sugar concentrations as categorical variables. The objective was to identify and discuss significant differences in pupil responses from one sample to another, thereby providing a broader perspective on the correlation between physiological response and sugar concentration.

The left graph (a) depicts clear zones where the samples with varying sugar concentrations exhibited different pupil responses compared to the water sample 0%. However, an interesting shift in the pattern emerged when water was excluded from the analysis, as shown in the right graph (b). Here, when comparing the pupil responses of the sample with the middle sugar concentration (30%) against the other sweetened samples, only small areas showed significant differences. This observation indicates that while there was a distinct physiological response to the presence of sugar as opposed to water, the differences in pupil dilation between samples with varying sugar concentrations were less pronounced.

This finding suggests that the overall correlation observed earlier in the study was predominantly driven by the contrast in response to water versus any sweetened sample, rather than by the variations in sugar concentration among the sweet samples. In essence, the presence of sugar, regardless of concentration, elicited a more pronounced physiological response compared to water, but the gradations in sugar concentration among the sweetened samples had a secondary role in this response.

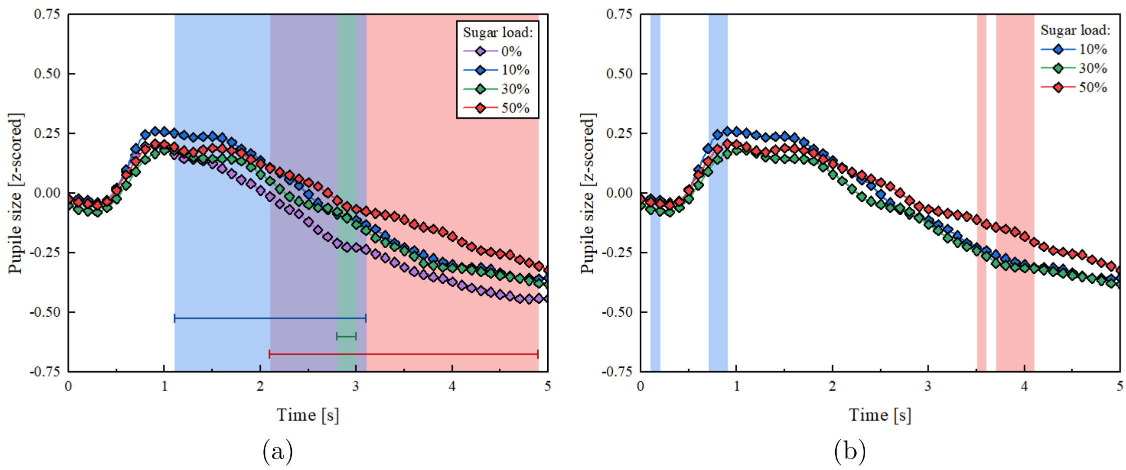


Figure 6.4: Mean pupil size curves of different sugar concentration samples (49 panellists in one sessions). Correlation modelled as a LME with sugar concentration marked with colored background indicating significance at level of 0.05. Colors correspond to the sample colors in comparison to reference (a) 0% (b) 30%.

Consumption protocol correlation

In Figure 6.5 the investigation into how consumption conditions, specifically active versus passive tongue movement, affect pupil size response added another layer of depth to the study.

Similar to the sensory results, the pupil dilation data was analyzed with respect to these two different consumption conditions. All samples of different concentrations were averaged together to emphasize this consumption effect. The statistical analysis revealed clear and broad areas where significant differences in pupil size response were observed between the samples tested under active tongue movement and those tested under passive tongue movement.

This finding is significant as it highlights the impact of the physical action of tasting on physiological responses. When participants were allowed to move their tongues actively while tasting (mimicking natural eating conditions), their pupil responses differed notably from those recorded when the tongue was kept still. These insights into the relationship between motor actions (like tongue movement) and sensory processing are invaluable for understanding the full spectrum of the eating experience.

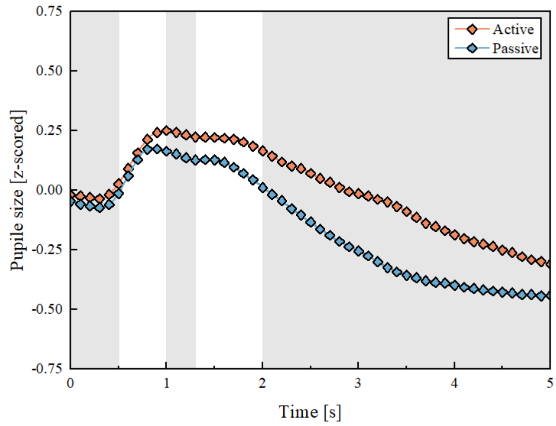


Figure 6.5: Mean pupil size curves with correlation modelled as a LME with consumption protocol marked with shaded background indicating significance at level of 0.05. (49 panellists in one sessions)

Fatigue effect

The exploration of potential fatigue effects during sensory testing is a critical aspect, especially considering how fatigue might influence both sensory responses and direct physical responses, such as eye dilation. In the analysis presented in Figure 6.6, both the averaged sweetness ratings and pupil sizes were plotted over the course of the testing period, encompassing a broad range of trial numbers. This approach allowed for the observation of trends that might indicate the impact of fatigue on the participants.

Interestingly, the sweetness ratings displayed an almost perfectly constant trend throughout the testing period. This consistency suggests that the perception of sweetness remained stable, unaffected by the progression of the trials. Nakagawa *et al.* (1996) reported that mental tasks shorten the perceived duration of sweet taste sensations and total amount of sweetness was also significantly reduced.

In contrast, the data for pupil size showed a steady decline with ongoing test duration. This trend is indicative of physical fatigue, as the task of continuously focusing and engaging in the testing process can be taxing on the body, particularly on the eyes and associated neurological mechanisms. Hopstaken *et al.* (2015) found that increasing mental fatigue is associated with diminished stimulus-evoked pupil dilation.

The divergence between the stable sensory response and the declining pupil dilation is noteworthy. It suggests that while physical fatigue was evident, it did not influence the participants' perception of sweetness. One possible explanation for this could be that the participants became more familiar with the samples over time, potentially recognizing and assessing them more easily as the trials progressed. This increased familiarity might have counteracted any potential fatigue effects on their sensory perception.

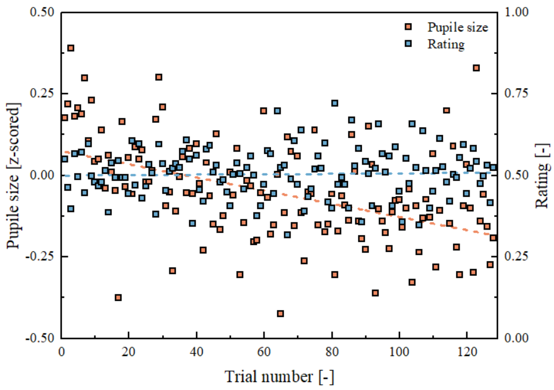


Figure 6.6: Averaged participant's pupil size and rating versus trial number. Linear fitting of the data sets (a) pupil size: slope at 0.05 level significantly different from zero $R^2 = 0.19$ (b) rating: slope at 0.05 level not significantly different from zero $R^2 = 0.01$. (49 panellists in one sessions)

6.1.3 Analysis of brain event-related potentials

Brain response in form of event-related potentials (ERP) were recorded to observe brain activity during sensory testing, providing a window into the neurological responses associated with taste perception. The use of 129 electrodes distributed around the participants' heads allowed for a comprehensive capture of these signals, which were then correlated with the sensory ratings of the different sugar concentration samples.

Sugar concentration correlation

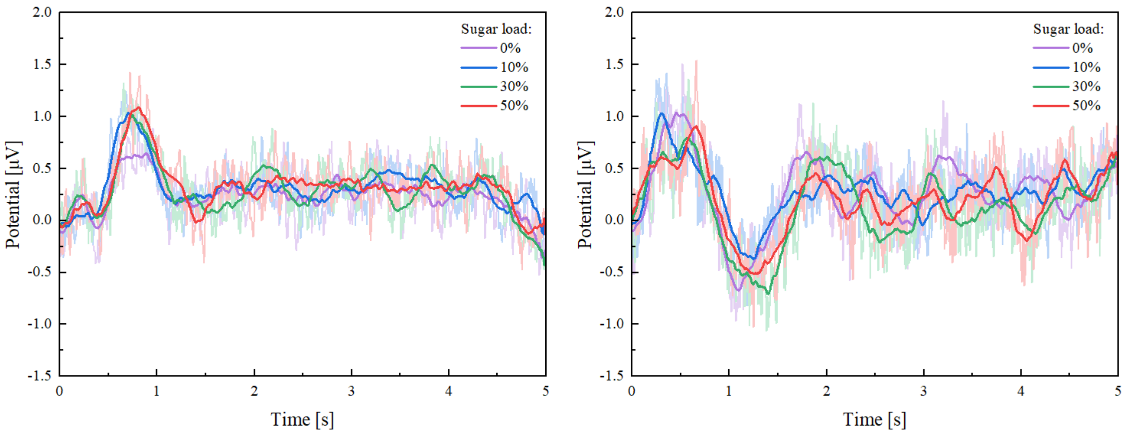
The analysis of these ERP curves in Figure 6.7 did not reveal any significant time points where the brain activity differed notably among the four sugar concentration samples. This lack of significant differentiation suggests that the varying sugar concentrations did not elicit distinctly different neurological responses that could be captured at specific moments in the ERP data.

Despite this, through visual evaluation of the ERP data, clusters of electrodes with similar response patterns were identified and grouped for discussion in this chapter.

"Cluster 1" was primarily selected for its differentiated responses to the sugar samples. This cluster also included electrodes that had been previously identified in literature as relevant to sweetness responses, offering a potential avenue to explore the neural processing of sweetness (Wilton *et al.*, 2019).

Second "Cluster 2" was identified based on variations in response to different viscosity samples, which are discussed later in the thesis. This cluster could provide insights into the neurological processing of texture in food.

While the lack of significant time points in the ERP data suggests a level of uniformity in brain response to different sugar concentrations, the visual analysis of these clusters offers an alternative approach to understanding the neurological underpinnings of taste perception. By examining the similarities and differences between these clusters, the study can delve into the subtleties of how the brain responds to various sensory stimuli, even when these differences are not starkly significant.



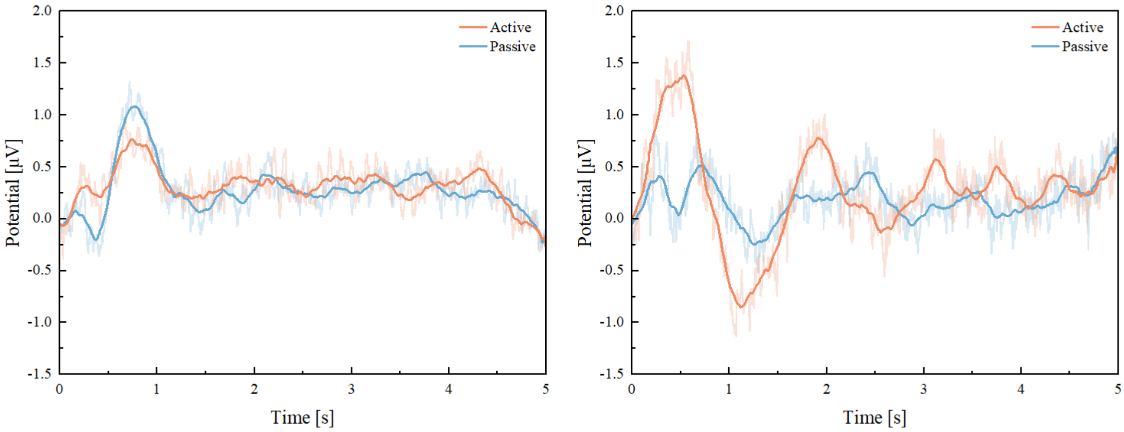
(a) cluster 1 (b) cluster 2

Figure 6.7: Event-related potential curves of different sugar concentration samples (49 panellists in one sessions). Adjacent-average smoothed curves with original mean values in background. Used electrode cluster indicated under graph.

"Cluster 1" exhibited a notable peak in brain activity occurring between 0.5 and 1 second after sample administration, potentially indicative of a response to the sugar samples. Interestingly, the response pattern for the water sample within this cluster was distinctly different compared to the other three sugar-containing samples. This partially matches a previous study where amplitude shift was dependent on taste intensity (Ohla *et al.*, 2012). This divergence mirrors the observations from the pupil response data, where the water sample also demonstrated the most significant difference in comparison to the sugar samples. Such a pattern suggests that the brain's response to the absence of sugar (as in the water sample) is neurologically distinct from its response to varying sugar concentrations.

For "Cluster 2" while clear peaks in brain activity were also evident, these seemed to be triggered by the mere application of the sample rather than by the sugar concentration itself. The lack of a clear visual trend correlating with sugar concentration in these cluster implies that the brain's immediate response to sample application is somewhat uniform across different sugar levels. This observation could suggest that the initial sensory input triggers a general neural response that is not finely tuned to the specific sugar concentration in the short term.

Consumption protocol correlation



(a) cluster 1 (b) cluster 2

Figure 6.8: Event-related potential curves of different consumption protocols (49 panellists in one sessions). Adjacent-average smoothed curves with original mean values in background. Used electrode cluster indicated under graph.

The investigation into the effects of tongue movement on ERPs revealed varying degrees of differences across the clusters as observed in Figure 6.8.

"Cluster 2," which was purposefully chosen to underscore electrodes demonstrating the most visual differences between differences in viscosity changes discussed in the next part of the study, emphasizes this aspect. The ERP curves from this cluster showed noticeable variations, suggesting that these selected electrodes could potentially capture the nuanced differences in sweetness perception when the tongue is either moving or stationary.

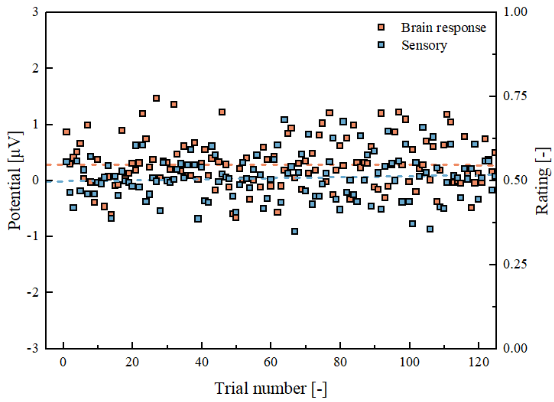


Figure 6.9: Averaged participant's pupil size and rating versus trial number. Linear fitting of the data sets (a) pupil size: slope at 0.05 level not significantly different from zero $R^2 = 0.01$ (b) rating: slope at 0.05 level not significantly different from zero $R^2 = 0.01$. (49 panellists in one sessions).

Fatigue effect

The analysis of fatigue effects on ERPs during the sensory testing brought to light some interesting contrasts with the findings from the pupil dilation study (Fig.6.9).

The sweetness ratings provided by participants showed no significant variation over time, indicating a stable sensory response throughout the testing period. However, in contrast to the findings from the pupil response study, the ERP data did not show a decline over time. This observation suggests that, from a neurological standpoint, the task of tasting and evaluating the samples was not as taxing as it was on the physical level. The lack of a declining trend in brain activity over the course of the testing indicates that the participants' brains remained consistently engaged and responsive to the sensory stimuli, without showing signs of fatigue that were evident in the physiological response of the eyes. Hord and Tracy (1984) reported that after sleep deprivation, the latency of visual sensory ERPs increases but amplitude is not affected. As the fatigue graph only represents average potentials, possible latency shift triggered by fatigue did not manifest.

This distinction between the brain's response and the eye's response to the testing task is intriguing. It highlights the different ways in which the body and brain can experience and manifest fatigue.

6.2 Sweetness percpetion under increased flow behavior

In the second part of the study, the focus shifted to investigating the influence of viscosity on sweetness perception. The underlying hypothesis was that increased viscosity reduces the perception of sweetness, and that this effect could be detected in both pupil response and brain response. In the work of De Celis Alonso *et al.* (2007) brain regions that are capable of detecting viscosity were already detectable.

The study involved testing sweetness perception across four levels of sugar concentration: 0% (representing the water sample), 10%, 20%, and 40%. To explore the impact of viscosity, two of these samples – the 0% water sample and the 20% sugar solution sample – were modified by the addition of xanthan gum to create two additional samples with increased viscosity but the same level of sugar.

6.2.1 Analysis of sensory responses

Sensory evaluation results shown in Figure 6.10, indicated that the sweetness perception of the pure sugar concentration samples differed significantly and increased in line with sugar concentration. For the behavior of the samples with added xanthan (increased viscosity), there was no significant difference in sweetness perception between the water sample with and without added xanthan, which aligns with expectations given the absence of sugar in these samples. In contrast, the 20% sugar sample with added xanthan exhibited a significantly lower sweetness perception compared to the same concentration without the viscosity modifier.

These results approximately align with the initial hypothesis that increased viscosity should lead to a reduced perception of sweetness, particularly in the sugar-containing sample Pangborn *et al.* (1973). The lack of significant change in the water samples also makes sense, as there was no sweetness to be perceived in the first place. This part of the study underscores the impact of textural attributes, such as viscosity, on the sensory perception of sweetness.

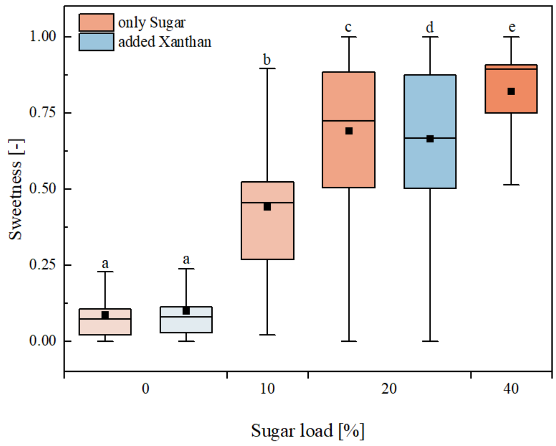


Figure 6.10: Perceived sweetness intensity during comparative profiling (26 panellists in one session). Samples indicate sugar concentration in wt%. Samples that do not share a letter are significantly different at the 0.05 level.

6.2.2 Characterization of physical properties

The study also included an analysis of the flow behavior of all samples to more precisely understand the level of viscosity change introduced by the addition of xanthan (Fig.6.11). It was observed that the samples containing no xanthan (0%, 10%, 20%, and 40% concentrations) exhibited lower viscosity compared to the samples with added xanthan. The pure sugar and water samples displayed a Newtonian flow profile, characterized by a consistent viscosity irrespective of changes in shear rate. This behavior is typical of simple sugar solutions or water.

In contrast, the incorporation of xanthan into the sugar solutions resulted in a notable shift to shear-thinning behavior, where viscosity decreases with increasing shear rate. This is a common characteristic of solutions with hydrocolloids like xanthan gum (Morris, 1994). Accepting this limitation was a necessary compromise in the study since achieving an increase in viscosity while maintaining a Newtonian flow profile proved challenging, particularly without altering the overall taste of the samples – a crucial factor for unbiased sensory evaluation.

While the increase in sugar concentration did lead to a slight rise in viscosity, this change was not as significant as that brought about by the addition of xanthan. When comparing the sugar samples without xanthan to their xanthan-enhanced counterparts, there was a obvious difference in viscosity. The xanthan-containing samples exhibited at least a thirtyfold increase in viscosity across the measured shear rate range.

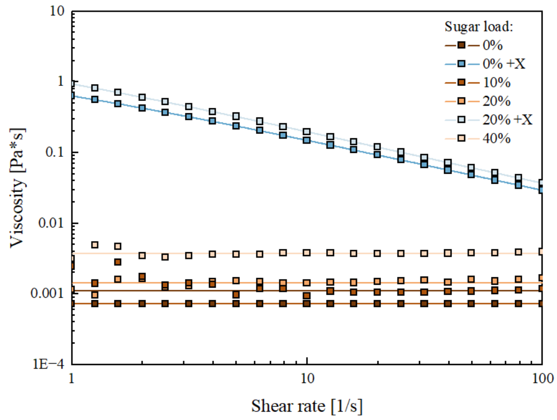


Figure 6.11: Viscosity curves at 40°C using a Couette geometry. Samples indicate sugar concentration in wt% with "X" for xanthan addition. All results were measured in triplicates. Curve fitting to highlight trend. N = 1.

6.2.3 Analysis of pupil dilation

Sugar concentration correlation

In the analysis of pupil data for the pure sugar samples presented in Figure 6.12, the correlation graph echoed the findings from the previous study.

When the water sample (0% sugar concentration) was used as a reference, the pupil responses of the three sugar-containing samples (10%, 20%, and 40% concentrations) displayed significant correlations with the sugar concentration at various points on the time scale. This finding indicates that the presence of sugar, as opposed to the absence of it in the water sample, elicited a distinct physiological response as measured by pupil dilation.

By focusing only on the three sugar-containing samples, the significance of the correlations largely disappeared. This shift suggests that while the presence of sugar in a sample can be distinguished from its absence (as in the water sample) based on pupil response, the differences in sugar concentrations within the range studied did not elicit significantly different responses in pupil size.

This pattern in the pupil data indicates that, for the sugar concentrations tested, the level of sweetness does not seem to significantly impact pupil dilation. The physiological response measured through pupil dilation is sensitive enough to detect the presence of sugar versus no sugar but does not appear to differentiate finely between varying concentrations of sugar. This observation is particularly relevant for sensory science, as it highlights the limitations and capabilities of physiological measurements like pupil dilation in reflecting subtle differences in taste stimuli.

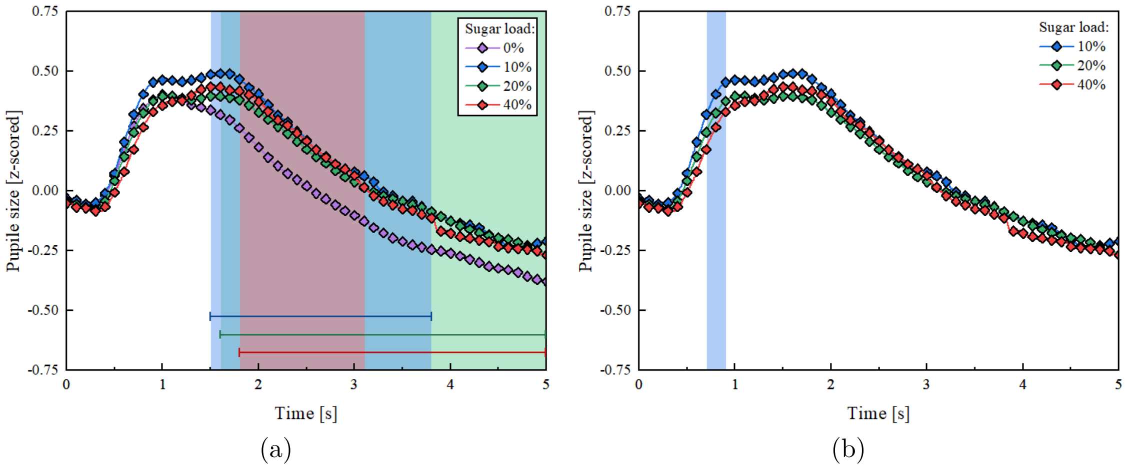


Figure 6.12: Mean pupil size curves of different sugar concentration samples (26 panellists in one session). Correlation modelled as a LME with sugar concentration marked with colored background indicating significance at level of 0.05. Colors correspond to the sample colors in comparison to refrence (a) 0% (b) 30%.

Flow behavior correlation

The examination of pupil size responses in the context of samples with and without added xanthan gum yielded fascinating results, when comparing the water sample (Fig.6.13a) to the 20% sugar sample (Fig.6.13b).

In the sensory evaluation, no significant difference in sweetness perception was noted for the water sample regardless of xanthan addition, while a significant reduction in perceived sweetness was observed for the 20% sugar sample with added xanthan. However, the pupil dilation data presented an intriguingly opposite trend.

The left graph (a), focusing on the water sample, showed differences in pupil dilation between the sample with and without added xanthan. Conversely, the right graph (b), representing the 20% sugar sample, exhibited almost identical pupil responses for both groups (with and without xanthan). This suggests that the participants' sensory focus on sweetness did not align with the eye response, which may react to another stimuli.

It appears that pupil dilation in this study was more sensitive to textural changes in the water sample but not in the sugar sample. This observation aligns with previous findings where water consistently evoked significantly different responses compared to sweetened samples. This indicates that while texture, as altered by xanthan addition, can elicit measurable changes in pupil response, it does not necessarily impact the sensory perception of other qualities like sweetness.

Interestingly, the addition of sugar to the samples seemed to mask the distinctiveness in pupil response to textural changes, further emphasizing the idea that in sugar-containing samples, pupil dilation is not nuanced enough to detect subtle differences. This outcome highlights the complexity of sensory perception, where various stimuli can elicit different responses across sensory modalities. It also underscores the potential of using pupil dilation as a complementary measure in sensory science, particularly for detecting responses to stimuli other than taste, such as texture. However, it also points to the limitations of this approach when the stimuli are more complex or when multiple sensory attributes are present.

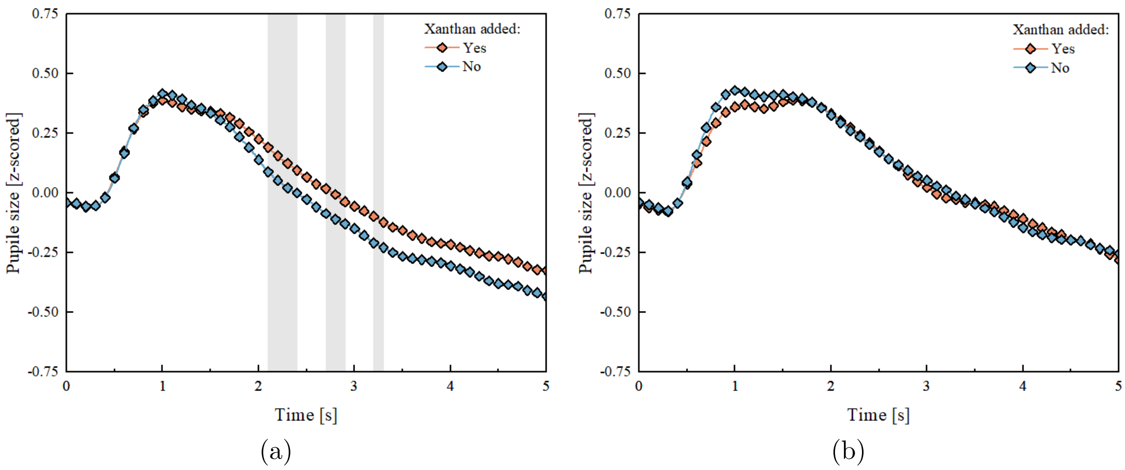


Figure 6.13: Mean pupil size curves of (a) water (b) 20% sugar samples with correlation modelled as a LME with presence of xanthan (26 panellists in one session). Marked with shaded background indicating significance at level of 0.05.

Fatigue effect

The effects of fatigue over the course of testing was monitored (Fig.6.14), and the trends observed were consistent with those seen in previous experiments.

There was no indication that the participants' ability to perceive and rate sweetness was affected by the duration of the testing. In contrast, a clear trend showing a reduction in pupil dilation is present. This pattern indicates that, despite the stability in sensory perception, the participants experienced physical fatigue, as evidenced by the diminished pupil response in the later stages of testing.

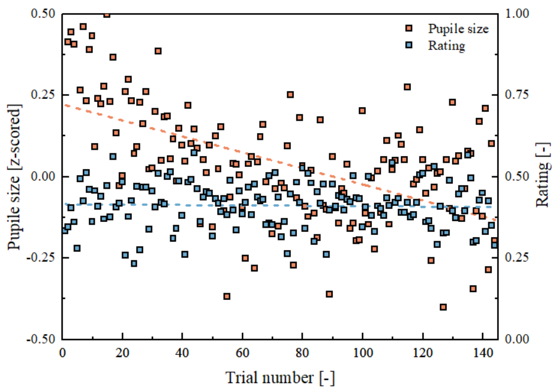


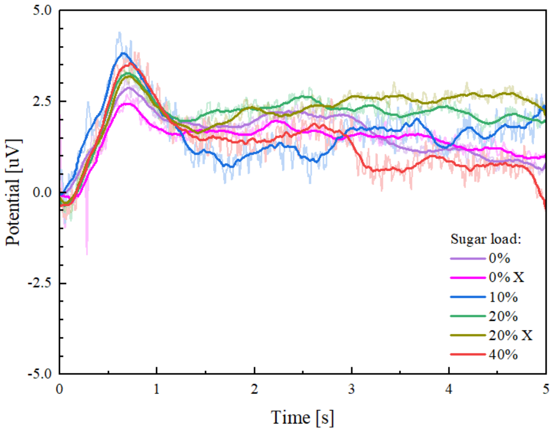
Figure 6.14: Averaged participant's pupil size and rating versus trial number. Linear fitting of the data sets (a) pupil size: slope at 0.05 level significantly different from zero $R^2 = 0.29$ (b) rating: slope at 0.05 level not significantly different from zero $R^2 = 0.01$. (26 panellists in one session)

6.2.4 Analysis of brain event-related potentials

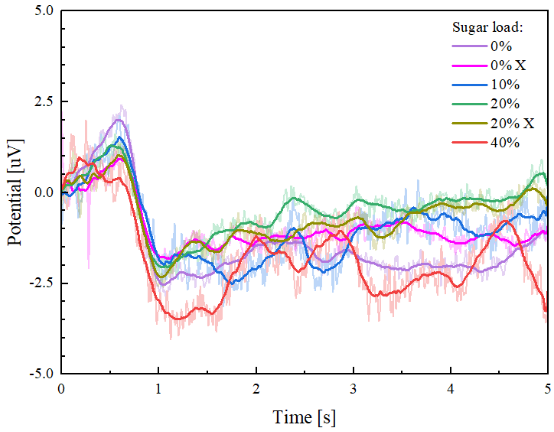
Sugar concentration correlation

When examining the ERP data across the different clusters identified in the study (Fig.6.15), no visual trends emerged that correlated with sugar concentration in "Cluster 1", which contradicts findings from literature were these electrodes could be correlated to sweet taste (Wilton *et al.*, 2019). This is particularly notable given the differences observed in pupil responses between the water sample and the sugar-containing samples in previous experiments. In this case, even the distinction between the water sample and the sugar samples in the ERP data was not as noticeable as it was in the previous experiment.

In "Cluster 2" the peak between 0.5s-1s may be of interst. Visiual observation seems to hint at a trend of lower peak height with increasing sugar content in the pure samples. The samples with xanthan do not follow any trend and are even collapsed onto eachother at this specific time point. As they are placed in the middle of the other samples, it cannot be concluded that the large viscosity difference is the cause of this placement.



(a) cluster 1



(b) cluster 2

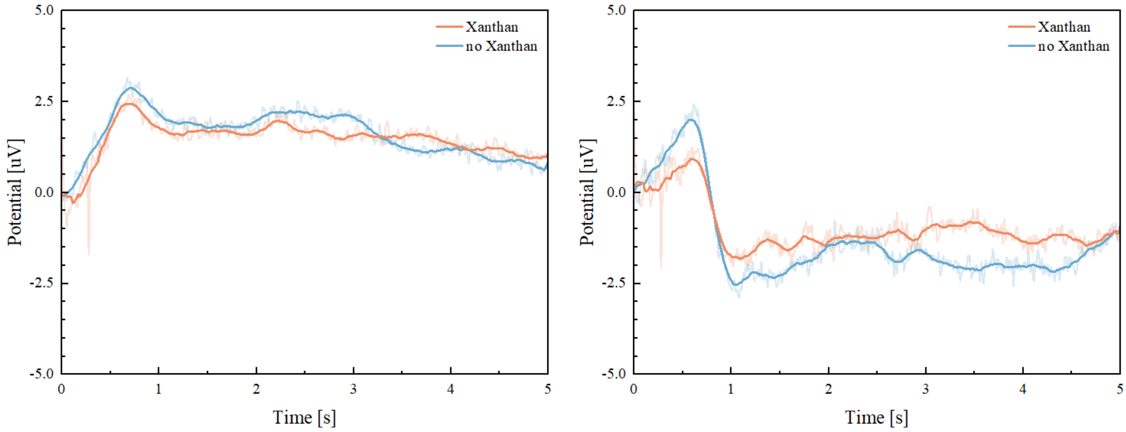
Figure 6.15: Event-related potential curves of different sugar concentration samples with and without added xanthan (26 panellists in one session). Adjacent-average smoothed curves with original mean values in background. Used electrode cluster indicated under graph.

These findings indicate that while certain physiological responses, like pupil dilation, can be sensitive to changes in stimuli such as sugar concentration and texture, these changes do not necessarily elicit a corresponding variation in brain activity detectable through ERPs. The absence of significant ERP differences across varying sugar concentrations and textures suggests that the brain's immediate electrical response to these gustatory stimuli is relatively uniform, at least in the aspects measured by ERPs.

Flow behavior correlation

The analysis of the event-related potentials (ERPs) under different flow conditions – with and without added xanthan gum – revealed some notable distinctions, particularly when considering the samples with no sugar shown in Figure 6.16 versus those with 20% sugar concentration (Fig.6.17). These observations were consistent across both identified clusters in the ERP data.

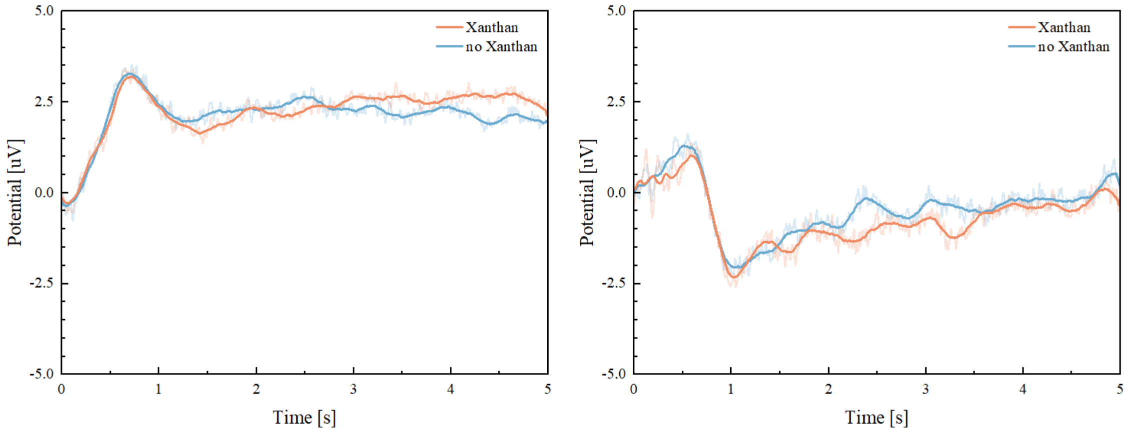
For the samples without sugar, a clearer difference in the ERP responses was observed between the samples with added xanthan than those without. This distinction was less pronounced in the 20% sugar samples, suggesting that the presence of sugar might mask or diminish the neurological response to changes in viscosity introduced by xanthan.



(a) cluster 1 (b) cluster 2

Figure 6.16: Event-related potential curves of the water sample with and without added xanthan (26 panellists in one session). Adjacent-average smoothed curves with original mean values in background. Used electrode cluster indicated under graph.

"Cluster 2" which was identified based on visual cues in electrodes that seemed to spotlight on viscosity effects, showed a more pronounced response in this context compared to "Cluster 1".



(a) (b)

Figure 6.17: Event-related potential curves of the 20% sugar sample with and without added xanthan (26 panellists in one session). Adjacent-average smoothed curves with original mean values in background. Used electrode cluster indicated under graph.

These ERP findings mirror the trends observed in the pupil response experiment, where the effects of xanthan were predominantly noticeable in the water samples. In both types of measurements – pupil dilation and ERPs – the addition of xanthan gum appears to elicit a more distinct response in the absence of sugar. When sugar is present, especially at higher concentrations like 20%, its influence seems to overshadow the textural effects of xanthan, leading to less differentiation in the neurological responses.

This pattern of results underscores the complex interplay between different sensory attributes – sweetness and texture – and how they are processed by the brain. The findings highlight that the brain's response to sensory stimuli can be significantly influenced by the specific combination of attributes present in a sample, and that certain attributes may dominate or modify the perception and neurological processing of others. This understanding is crucial for sensory science, providing insights into how consumers perceive complex food products with multiple sensory characteristics.

Fatigue effect

A quick assessment of potential fatigue effects during the ERP measurements reinforced the observations from earlier phases of the study (Fig.6.18).

There was no significant impact of fatigue on either the brain responses or the sensory responses over the duration of the testing.

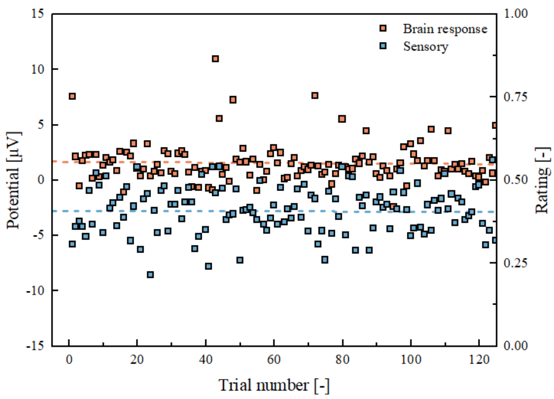


Figure 6.18: Averaged participant's pupil size and rating versus trial number. Linear fitting of the data sets (a) pupil size: slope at 0.05 level not significantly different from zero $R^2 = 0.01$ (b) rating: slope at 0.05 level not significantly different from zero $R^2 = 0.01$. (26 panellists in one session)

6.3 Effect of intensity and hedonic rating on pupil responses

In this final neuroscientific study, the focus pivoted to exploring the relationship between sensory-evaluated stimulus intensity and hedonic (pleasure-related) ratings. The primary objective was to discern whether pupil responses are more influenced by an increase in the intensity of a stimulus or by its hedonic liking.

6.3.1 Sample selection and design overview

To investigate this, four samples were selected, each representing different combinations of taste qualities and concentrations. These samples comprised two tastes – bitter and sweet – each available in high and low concentrations.

The design of the study was such that one tastant (sweet), at high concentration, was expected to score high on hedonic liking, while its lower concentration version was anticipated to rate lower on both intensity and hedonic liking.

The other tastant (bitter), at high concentration, was presumed to score low on hedonic liking, with its lower concentration counterpart rated higher on the hedonic scale, though lower in intensity.

This sample selection aimed to create a diverse range of sensory experiences, combining both the aspects of intensity and hedonic value in varying degrees.

In the graphical representation of the results presented in Figure 6.19, with intensity on the y-axis and hedonic ratings on the x-axis, the design of the sample selection was expected to yield a “V-shaped” distribution. Such a distribution would visually represent the inverse relationship between intensity and hedonic liking for one tastant and the direct relationship for the other.

By analyzing pupil responses to these samples, the study sought to determine whether the physiological reactions are more aligned with the intensity of the stimuli or their hedonic value. This approach is insightful as it delves into the complex interplay between the objective intensity of a sensory stimulus and its subjective hedonic perception, and how these are processed and reflected in physical responses like pupil dilation.

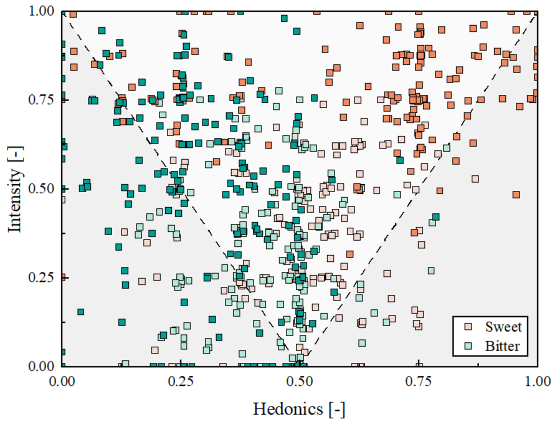


Figure 6.19: Average rating distribution overview in regards to intensity and hedonics (27 panellists in one session). Darker shades indicate higher concentration samples. In the background the experimental "V-shaped" design is highlighted.

6.3.2 Analysis of sensory responses

The sensory evaluation shown in Figure 6.20 yielded clear and significant differences among all four samples, both in terms of hedonic (liking) and intensity ratings. These results validated the study's design and hypothesis, confirming that the chosen samples effectively represented the intended variations in taste quality and concentration.

In terms of intensity, the results were consistent with expectations: the higher concentration samples were consistently rated as more intense than their lower concentration counterparts. This outcome aligns with basic principles of sensory perception, where an increase in the concentration of a tastant typically leads to a heightened perception of its intensity.

Regarding hedonic ratings, the bitter tastant was more preferred in its lower concentration, whereas the sweet tastant garnered higher hedonic ratings in its higher concentration. This pattern confirms the study's hypothesis that hedonic liking varies inversely with intensity for certain flavors like bitterness and directly for others like sweetness. This is also mentioned by Pfaffmann (1980) who notes that bitterness is mostly perceived as increasingly unpleasant, while sweetness is mostly perceived as increasingly pleasant.

These results from the sensory evaluation offer a nuanced understanding of how different concentrations of sweet and bitter tastants are perceived in terms of both

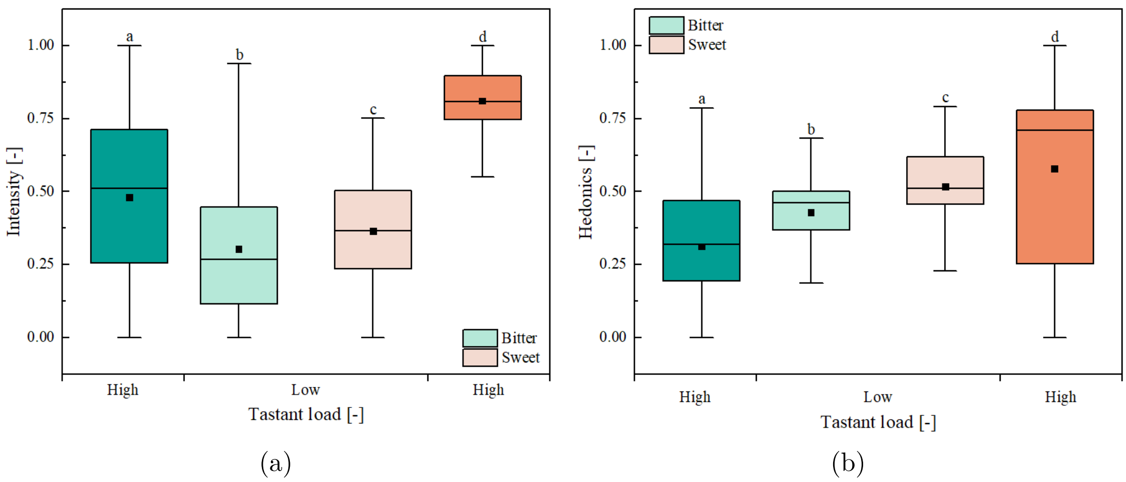


Figure 6.20: Perceived tastant (a) intensity (b) hedonics during comparative profiling (27 panellists in one session). Samples indicate level of tastant. Samples that do not share a letter are significantly different at the 0.05 level.

their intensity and their pleasantness. The study successfully demonstrates the complex relationship between the objective properties of a stimulus (like concentration) and its subjective sensory evaluation (intensity and hedonics). This knowledge is valuable in the context of food product development and flavor profiling, where balancing the intensity and hedonic appeal of different ingredients is key to creating products that are both flavorful and appealing to consumers.

6.3.3 Analysis of pupil dilation

The analysis of pupil dilation in response to the four different samples provided identification of specific timeframes during which the correlation between the sensory stimuli and pupil dilations were significant (Fig.6.21). These distinct timeframes, where the pupil responses to the four samples diverged from each other, presented an opportunity for a more in-depth exploration of what factors might be driving these differences.

By pinpointing these significant zones of pupil dilation, the study could delve deeper into understanding how various sensory attributes of the samples – such as their intensity, hedonic value, and specific taste qualities (bitter or sweet) – influenced physiological responses. The temporal aspect of these responses is particularly important, as it can shed light on the dynamics of sensory processing and perception.

For instance, if pupil dilation was more pronounced or occurred earlier for certain samples, it might suggest that those samples were either more intense or elicited a stronger hedonic reaction. Conversely, a delayed or reduced pupil response could indicate a less intense or less hedonically pleasing stimulus.

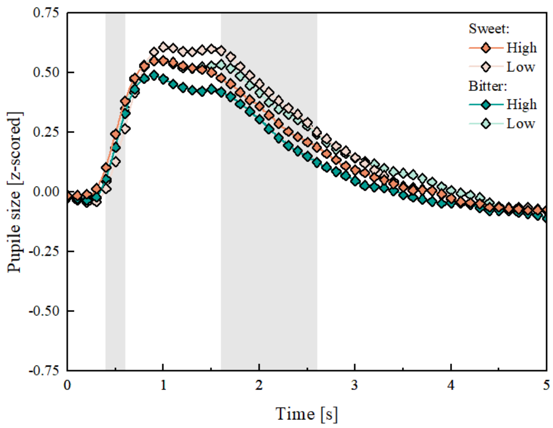


Figure 6.21: Mean pupil size curves of different tastants and concentration samples (27 panellists in one session). Correlation modelled as a LME with intensity rating marked with shaded background indicating significance at level of 0.05.

By grouping the data into specific comparison pairs like the type of tastant, its intensity, and hedonic ratings, the study aimed to uncover the underlying reasons for variations in pupil responses.

Taste correlation

When comparing the average responses of sweet versus bitter samples seen in Figure 6.22a, a notable segment with significant differences was observed, especially at the peak of eye dilation. This clear distinction indicates that participants were physiologically able to differentiate between sweet and bitter tastes.

Intensity correlation

Further, the analysis involving the averaged low and high concentration samples presented in Figure 6.22b revealed a more extended period of significant difference in pupil dilation. This pattern suggests that the concentration or intensity of the sample had a considerable impact on the eye's response, with different levels of concentration prompting varied degrees of pupil dilation.

Hedonics correlation

However, the comparison based on hedonic ratings (low vs. high liking) yielded a different picture (Fig.6.22c). The averaged samples for high and low hedonic ratings displayed almost no significant zones of difference in pupil dilation, except during the highly dynamic initial phase right after sample application. This lack of significant variation implies that hedonic liking had a minimal effect on the physiological eye response to the stimuli.

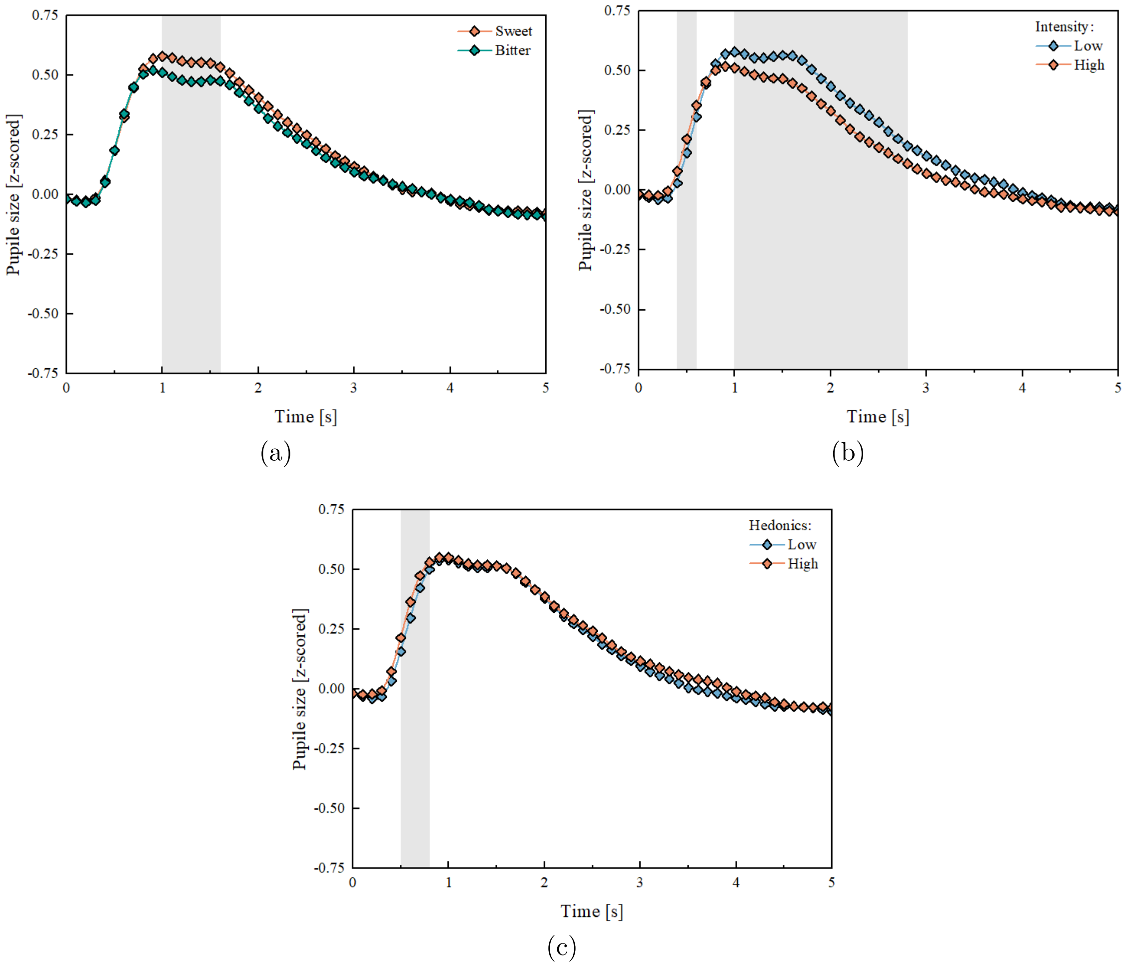


Figure 6.22: Mean pupil size curves of different (a) tastant (b) intensity (c) hedonics samples averaged (27 panellists in one session). Correlation modelled as a LME with the samples' focus. Marked with shaded background indicating significance at level of 0.05.

From these observations, it emerges that pupil dilation in response to gustatory stimuli is predominantly driven by the intensity of the sample, while the hedonic aspect (liking) plays a minimal or insignificant role in influencing the eye's response. Similar findings were published by Schneider *et al.* (2009) regarding olfactory triggers and van Hooijdonk *et al.* (2019) for touch-induced cues. These findings are critical as they underscore the primary factors affecting physiological responses in taste perception, highlighting that stimulus intensity is a more influential factor than hedonic evaluation in eliciting measurable physiological reactions. This insight is valuable for understanding the dynamics of sensory perception and can inform future research in areas related to sensory science and consumer behavior.

Rating task correlation

An intriguing other aspect of the study involved analyzing the potential influence of the rating task itself on pupil response as presented in Figure 6.23. The idea was to investigate whether the expectation of providing a rating after tasting a sample could affect the physiological response, as measured by pupil dilation.

To explore this, the study was designed so that only half of the trials included a rating step following the sample tasting. The other half were conducted without asking participants for a rating afterward. This approach allowed for a comparison between trials where the participants anticipated a rating task and those where they did not, providing insight into whether and how the expectation of rating influences physiological responses.

If it were found that pupil responses differed significantly between these two conditions, it would suggest that the anticipation or cognitive load associated with the rating task might be a confounding factor in measuring pure sensory responses through pupil dilation. On the other hand, if no significant differences were observed, it could indicate that pupil dilation is a reliable measure of sensory response independent of the cognitive processes involved in rating.

The comparison between trials where participants were asked to provide a rating and those without a subsequent rating task revealed significant differences in pupil size responses, offering insights into how the expectation of a rating influences physiological reactions.

Upon averaging all trials that involved a rating step and contrasting them with the trials that didn't include this step, a distinct pattern emerged. Both sets of trials exhibited a similar initial increase in pupil size following the stimulus application,

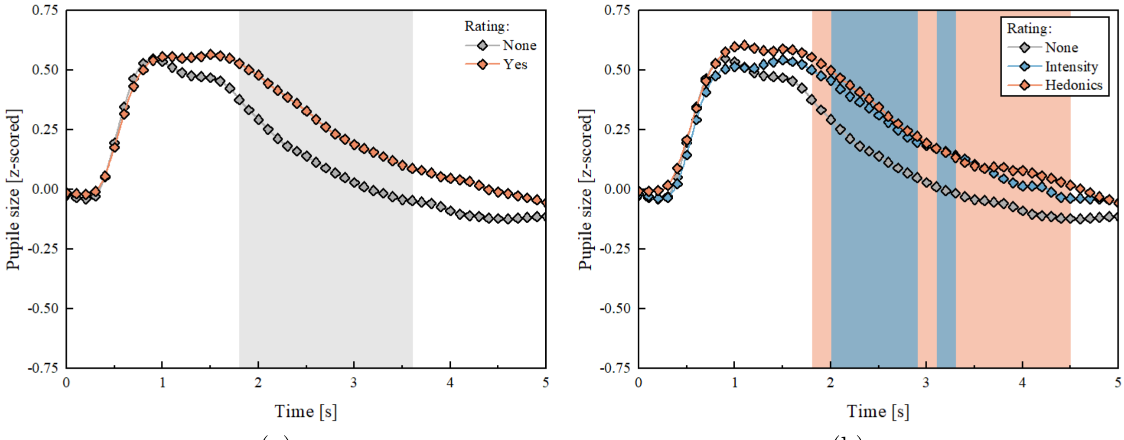


Figure 6.23: Mean pupil size curves of different rating task samples averaged (27 panellists in one session). Correlation modelled as a LME with the (a) rating versus no rating (b) intensity/hedonics rating versus no rating. Marked with shaded background indicating significance at level of 0.05.

but the trials without a subsequent rating step showed a significantly quicker relaxation phase. This suggests that the anticipation or cognitive processing involved in preparing to rate a sample may prolong the physiological response as measured by pupil dilation. Further analysis comparing the non-rated trials against those split into hedonic and intensity categories revealed interesting nuances. The difference in pupil response was more pronounced when compared to the hedonic rating trials. In contrast, the intensity rating trials demonstrated a period of difference primarily at the beginning of the significant timeframe, indicating that the influence of anticipating an intensity rating might be more transient.

These observations suggest that the cognitive load or expectation associated with the rating task affects the physiological response during sensory testing. The faster relaxation in pupil size in non-rated trials could indicate a reduced cognitive engagement or a more straightforward processing of the sensory experience when the task of rating is absent. In a study by Goldinger and Papesh (2012) they found that pupils typically dilate as cognitive demand increases.

This finding has important implications for sensory science methodologies. It indicates that while physiological measures like pupil dilation can provide valuable insights into sensory perceptions, they can also be influenced by the cognitive demands of the testing protocol, such as the expectation of providing feedback. Understanding this interaction is crucial for designing sensory tests that accurately capture the innate sensory responses of participants, potentially leading to the development of more streamlined and objective sensory evaluation methods.

7 Correlation of panel characteristics with their sensory responses

In this last chapter the personal data provided by participants during the previous sensory experiments are analyzed and discussed. This data encompasses a broad spectrum of variables, including eating and drinking habits, weight and height, gender, smoking habits, and other personal information. The purpose of this comprehensive data collection is to explore potential correlations between these personal attributes and the sensory responses observed for the participants. The selection of questions was based on the standard questionaire destributed in the neuroscience lab at ETH Zürich, where these sensory trials were conducted. Although the exact age of the participants was not recorded, it should be noted that the study generally attracted participants who were students on campus and therefore the age range was lower than that of the general population.

7.1 Grouping participants based on personal characteristics

By correlating the sensory responses with these key personal characteristics seen in Figure 7.1, the study aims to identify possible groupings among the participants. These groups could signify shared characteristics or behaviors that may account for variations in sensory evaluation. The identification of such groups is crucial, as it could reveal common underlying factors that influence how individuals perceive sensory stimuli.

For instance, factors like dietary habits, body composition, or lifestyle choices (such as smoking) might have a significant impact on sensory perception. By analyzing how these personal variables relate to the way participants respond to gustatory stimuli, the study can uncover patterns that might explain differences in taste sensitivity, preference, or perception.

In discussing the correlations between personal data and sensory responses, it's crucial to emphasize that correlation does not always imply causation. This means that while significant relationships can provide valuable insights, they should not be interpreted as definitive evidence of cause-and-effect relationships. This caution

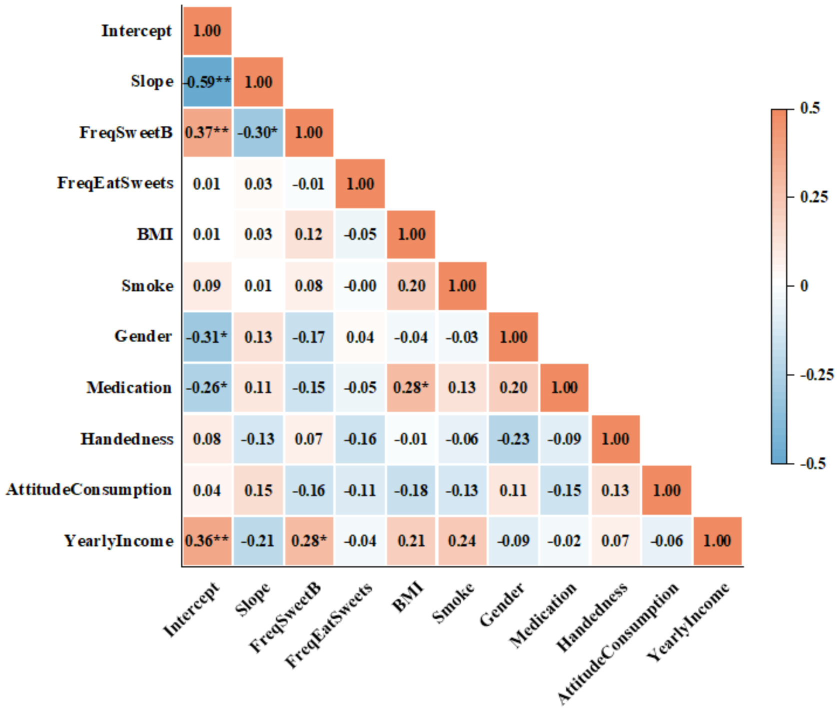


Figure 7.1: Correlation table with correlation coefficients comparing sensory evaluations and panelist characteristics to tongue topography properties. ** refers to a significance level of 0.01 and * to a significance level of 0.05.

is particularly pertinent in sensory science, where a multitude of factors can influence perception. A linear fitting approach was applied to the previously discussed samples of different sugar concentrations.

7.2 Analysis of sensory responses across different groups

7.2.1 Consumption frequency of sweet beverages

Specifically, a noteworthy observation was made regarding the frequency of consuming sweet beverages shown in Figure 7.2. There was a significant positive correlation with the intercept, indicating that participants who frequently consumed sweet drinks tended to rate the lower sugar concentration samples higher initially, compared to those who consumed sweet beverages less often. This suggests that habitual consumption of sweet drinks might influence the baseline perception of sweetness, potentially due to a heightened sensitivity or acclimatization to sweet tastes. Conversely, the significant negative correlation with the slope suggests that this initial heightened perception diminishes as the sugar concentration increases. This could imply that regular consumers of sweet beverages might experience a sort of 'taste fatigue' or reduced sensitivity to differences in higher sugar concentrations, as they are already accustomed to high levels of sweetness in their diet.

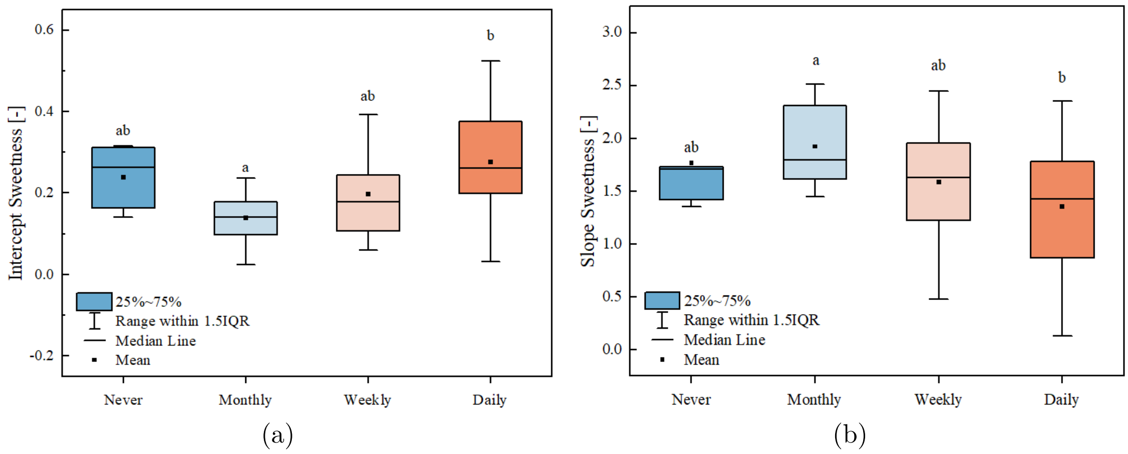


Figure 7.2: Fitted sweetness (a) intercept (b) slope grouped into frequencey of sweet drinks conumption (49 panellists). Groups that do not share a letter are significantly different at the 0.05 level.

While the differences in sensory perception between these groups were not significant across the board, from high to low the groups showed the aforementioned relationships to the sensory behavior. In the study of Sartor *et al.* (2011) participants underwent a four week period of increased sucrose solution consumption and they found that sucrose intensity scores significantly increased with increasing concentration.

However, an interesting deviation from this trend was noted among participants who reported no consumption of sweet drinks. This group did not fit into the observed pattern, suggesting a different relationship between their sweet drink consumption habits (or lack thereof) and their sensory perception of sweetness.

7.2.2 Consumption frequency of sweet foods

The observation that participants' habits of eating sweet food did not correlate with their sensory responses to the sugar concentration samples is intriguing, especially when contrasted with the significant correlations found with sweet beverage consumption (Fig.7.3).

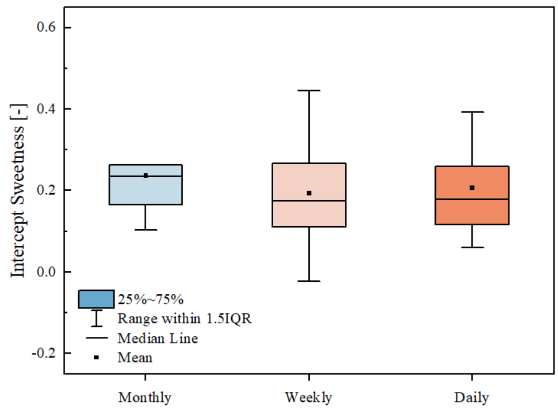


Figure 7.3: Fitted sweetness intercept grouped into frequencey of sweet foods conumption (49 panellists). Groups that do not share a letter are significantly different at the 0.05 level.

One plausible explanation for this discrepancy could be related to the form in which the samples were presented during the sensory trials. Since the samples were in liquid form, it's possible that the participants' experiences and habits with sweet beverages were more directly applicable and influential in their sensory evaluation of the liquid samples.

7.2.3 Body Mass Index

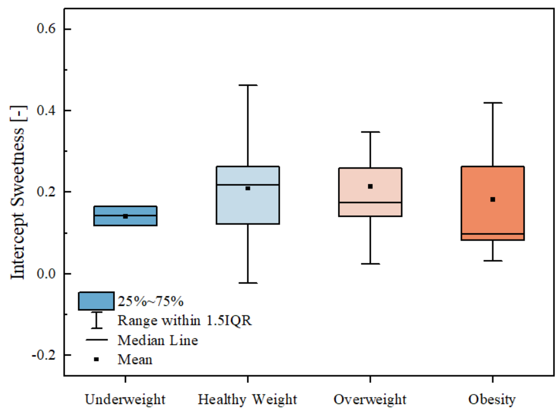


Figure 7.4: Fitted sweetness intercept grouped into BMI categories (49 panellists). Groups that do not share a letter are significantly different at the 0.05 level.

Incorporating weight and height data to calculate Body Mass Index (BMI) scores for the participants was a methodical attempt to explore potential correlations between BMI and sweetness perception. However as observed in Figure 7.4, the analysis revealed no significant correlation between participants' BMI scores and their ratings of sweetness. This finding indicates that BMI, as an indicator of physical health or body composition, did not appear to influence how individuals perceive the sweetness of the samples tested in this study. In contrast Sartor *et al.* (2011) found in their study that overweight-obese subjects tasted sweet sucrose solutions 23% less intense than normal-weight subjects.

7.2.4 Frequency of smoking habit

The influence of smoking habits on taste perception is a topic of interest in sensory science, given the potential impact of smoking on the olfactory and gustatory systems. In this study, the correlation between the frequency of smoking and the ability to rate sweetness was analyzed, aiming to determine whether smoking habits influence how sweetness is perceived.

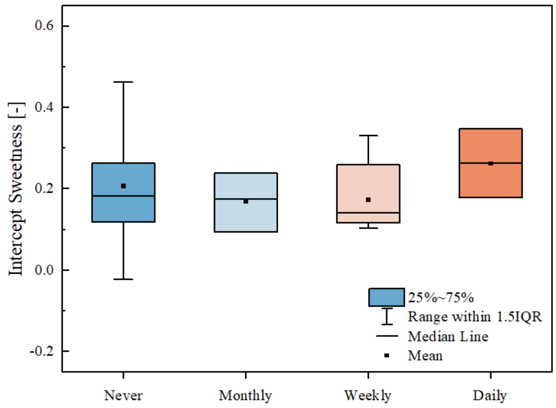


Figure 7.5: Fitted sweetness intercept grouped into frequencey of smoking habit (49 panellists). Groups that do not share a letter are significantly different at the 0.05 level.

The analysis across the different groups of participants seen in Figure 7.5, from non-smokers to heavy smokers, revealed no significant correlation between smoking habits and sweetness perception. This finding suggests that, within the context of this study, smoking did not notably affect the participants' ability to perceive and rate the sweetness of the samples. Pepino and Mennella (2007) found that smoking women had lower sensitivity to sweet tastes. But Guido *et al.* (2016) found that smoking did not significantly influence sweet taste perception.

It needs to be mentioned that the participants were asked to refrain from smoking before coming to the sensory session. This period of abstinence may have already been sufficient to negate any inhibiting effects smoking could have on sensory perception.

7.2.5 Gender

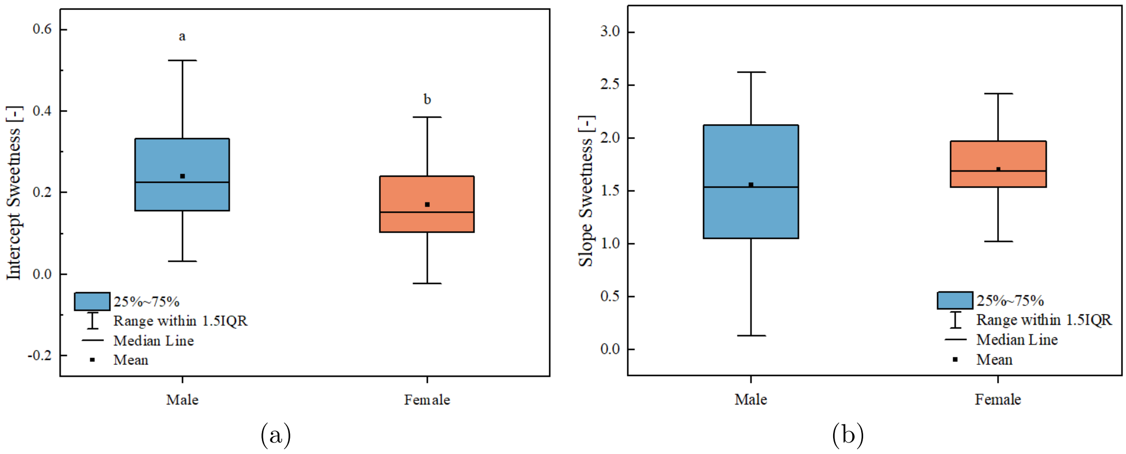


Figure 7.6: Fitted sweetness (a) intercept (b) slope grouped into genders (49 panellists). Groups that do not share a letter are significantly different at the 0.05 level.

The analysis of gender differences in sweetness perception presented in Figure 7.6, revealed significant variations. A notable finding was that male participants, on average, had a higher intercept in their sweetness ratings. This suggests that males tended to rate the sweetness of samples higher than females, indicating a gender-based difference in baseline sweetness perception.

Looking at the slope, which represents the rate of change in sweetness perception across different sugar concentrations, no significant difference was observed between males and females. This implies that while males generally rated sweetness higher than females, the way both genders perceived the increase in sweetness with higher sugar concentrations was similar. In other words, the rate at which sweetness perception intensified with increasing sugar content was consistent across genders.

Literature does not provide a conclusive statement on the topic. Thai *et al.* (2011) reported that the intensity perception and pleasantness of most sweet solutions were not significantly associated with gender. While Furquim *et al.* (2010) found that sensitivity to bitter taste and sweet taste perception is significantly associated with gender. Also Michon *et al.* (2009) observed gender differences in sweet intensity assessments.

7.2.6 Medication

In the study, the inclusion of medication usage as a factor was primarily driven by the standard questionnaire used in the neuroscience lab where the experiments were conducted. While the impact of medication on brain responses is an area of interest in neuroscience, its influence on sensory perception, particularly sweetness perception, is less clear.

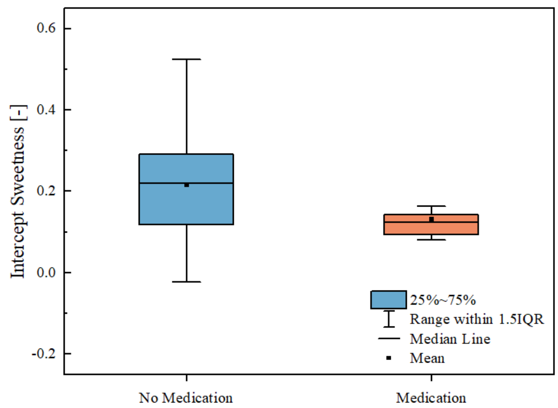


Figure 7.7: Fitted sweetness intercept grouped into medication usage (49 panellists). Groups that do not share a letter are significantly different at the 0.05 level.

The analysis in Figure 7.7 revealed that participants who were on medication during the testing period had significantly lower intercept values in their sweetness ratings compared to those not on medication. This suggests that medication usage might be associated with a lower baseline perception of sweetness. However, it's crucial to approach this finding with caution.

The robustness of this statistical finding may be questionable, given the uneven distribution of participants into the two groups (medication vs. no medication). With only 9 out of 67 participants being on medication, the sample size for this subgroup is relatively small. This limited sample size can affect the reliability and generalizability of the results, as it may not adequately represent the broader population.

In summary, while the finding regarding medication usage and sweetness perception is interesting and adds to the completeness of the study, it should be interpreted with caution. The potential influence of medication on sensory perception is a complex area that warrants further investigation, ideally with larger and more evenly distributed samples to enhance the statistical robustness and generalizability of the findings.

7.2.7 Yearly income

The analysis between participants' yearly income and their sweetness ratings shown in Figure 7.8 indicated a significant influence of income on the general rating of sweetness, with a trend showing that higher income corresponded to higher ratings on the sweetness scale.

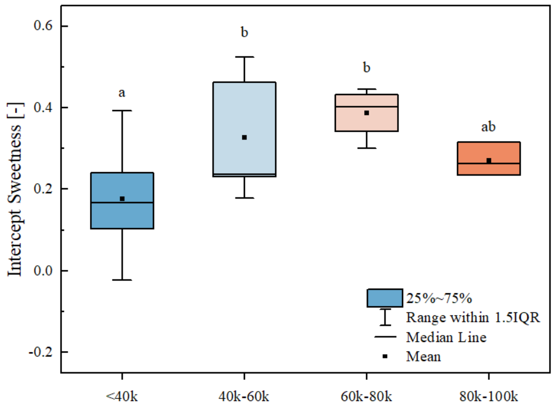


Figure 7.8: Fitted sweetness intercept grouped into yearly income brackets (49 panellists). Groups that do not share a letter are significantly different at the 0.05 level.

However, the detailed graph depicting this correlation revealed a nuanced pattern. While the trend of increasing sweetness ratings with rising income held true from the low to middle-high income brackets, the highest income group showed a reduced intercept. This deviation suggests that the relationship between income and sweetness perception is not straightforward and may involve other underlying factors.

Literature did not provide insight in the influence of income on sweetness perception directly. However, studies have shown that taste preferences and food choices, which could include preferences for sweetness, are linked to economic variables such as income (Drewnowski, 1997). Moreover, Jamel *et al.* (1996) found that individuals from urban locations show a higher preference for sweetness. And urbanization often correlates with higher income levels.

It is important to note that the distribution of participants across the different income categories was very skewed, with about 80% of the participants falling into the lowest income bracket. This skewness is not surprising, considering that many participants were neuroscience students, likely with lower income levels, seeking practical experience in their field of study. The overrepresentation of lower-income participants could potentially affect the generalizability of the findings to a broader, more economically diverse population.

For future studies, enhancing the statistical robustness by including a more diverse range of participants in terms of income could be beneficial. Inviting individuals already working in industry, or even professors, could provide a more balanced distribution across income brackets. Such diversity would not only strengthen the findings but also offer a more comprehensive understanding of how socioeconomic factors like income might influence sensory perception.

8 Conclusions

In the pursuit of advancing our understanding of the frictional behavior of chocolate, this thesis details the design and implementation of a custom geometry specifically tailored for analyzing solid chocolate samples. The goal was to facilitate the investigation of the frictional behavior of non-homogeneous phase chocolate samples, a domain that standard tribological measurements have limitations in addressing.

The first set of measurements conducted with solid chocolate samples using this custom geometry provided valuable insights, particularly when compared to standard tribological measurements. These initial experiments were crucial in demonstrating the effectiveness and relevance of the custom geometry in capturing the frictional behavior of chocolate.

A notable observation was the inversion of the frictional response of the three model chocolates when transitioning from standard to custom geometry. This inversion highlights the significance of considering the solid-like structure of the samples in the custom geometry, which more accurately reflects the real conditions of chocolate consumption.

One of the key findings from the measurements using the custom geometry was the correlation with the sensory perception of smoothness. Qualitative comparisons revealed that the model chocolate with the lowest sugar content exhibited a higher friction factor in the sensory-relevant velocity range. This increased friction factor was associated with a lower perceived smoothness in sensory tests, as compared to the other chocolates. This correlation between the frictional behavior and sensory smoothness perception is a significant step forward in understanding the textural attributes of chocolate

In addition the development of a custom geometry for the frictional analysis of solid chocolate represents a significant advancement in the field of sensory science and food technology. By enabling more accurate and relevant measurements of the frictional behavior of chocolate, this approach provides a deeper understanding of how textural attributes like smoothness are perceived. The findings from this chapter not only contribute to the scientific understanding of chocolate's sensory attributes but also have practical implications for food product development and quality control in the chocolate industry. The integration of such custom methodologies could pave the way for more nuanced and precise approaches to evaluating and enhancing the sensory qualities of chocolate and other food products.

In the second chapter the study explores an innovative approach to enhancing the perception of sweetness in chocolate, employing inkjet printing to create patterns of thaumatin-filled dots. This technique contrasts with traditional methods where sweeteners are uniformly distributed throughout the product. The goal was to significantly boost perceived sweetness during consumption without increasing the total amount of sweetener.

The surface patterns led to a substantial enhancement in perceived sweetness, with an increase up to 300% during consumption. This remarkable improvement underscores the potential of this method in altering taste perceptions. It was observed that the proximity of these thaumatin concentrations to the taste buds, along with the physical processes and cognitive mechanisms involved in taste perception, played a crucial role in this enhancement.

Further, we examined how concentrating thaumatin-filled dots in the center or periphery of the sample affected overall sweetness perception. It was observed that sweetness perception decreased when thaumatin was absent from certain areas of the tongue, particularly the tip, indicating the local taste sensitivity of the tongue.

This research presents a novel method for food manufacturers to enhance taste perception using local gradients and visually attractive surface designs. The inkjet printing technique offers a precise and adaptable tool for sensory modification, allowing more flexibility in modifying perception by adjusting patterns and dot density.

The investigation highlights the significance of spatially distributed stimuli in taste perception, setting the stage for future research in this exciting and evolving field.

Finally the neuro chapter explored the sensory response to stimuli of varying modalities, intensities, and viscosities. The research focused on monitoring pupil size and brain activity, specifically using pupillometry and electroencephalography (EEG), to understand how these different stimulus characteristics affect sensory perception.

Investigating the traditional beliefs about the relationship between viscosity and sensory intensity, the study found that this association was not totaly confirmed. While sensory differentiation was apparent for varying concentrations of sweetness, the corresponding pupil data did not align with the trends observed in sensory ratings. This discrepancy suggests a more complex relationship between sensory perception and physiological responses than previously understood.

Pupillometry, the measurement of pupil size, proved effective in differentiating between sweet and non-sweet stimuli. The study observed that pupil dilation varied with the sweetness of the stimuli, offering insights into the relative sensory characteristics of each sample. For waterbased samples with different viscosities, a trend in pupil size was noted, indicating a potential link between viscosity and pupillary response.

The EEG data demonstrated no significant dependence on the intensity of sweetness, with brain activity varying in response to different levels of sweet stimuli only visually and so far not statistically proven. The effect of viscosity on brain activity was even less clear, with only preliminary indications observed. This finding suggests the need for further investigations to fully understand the impact of viscosity on both pupil size and brain activity.

An intriguing observation from the second experiment was that pupil dilation appeared more responsive to the intensity of stimuli rather than their hedonic value. This chapter contributed significantly to the understanding of how different sensory stimuli characteristics influence physiological responses. The findings indicate a complex interplay between stimulus modality, intensity, viscosity, and sensory perception, as reflected in both pupillary and brain responses. The insights gained from this study open new avenues for sensory research, highlighting the potential of pupillometry and EEG as tools for investigating the nuanced responses to sensory stimuli. Further research is necessary to unravel the intricate relationships between sensory characteristics, physiological responses, and perceptual experiences, ultimately enhancing our understanding of sensory perception and its underlying mechanisms.

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