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Doctoral Dissertation

Investigating the Relationship Between Visual Food Stimuli and Appetite Behavior Using fNIRS Indicators

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Abstract

This study aimed to explore the relationship between visual food stimuli and appetite-related behaviors within the framework of the Stimulus-Organism-Response (SOR) model, employing functional near-infrared spectroscopy (fNIRS) to examine metabolic responses. We developed and validated a biological food preference task that simultaneously assesses physiological responses to various visual food stimuli and subjective evaluations of these foods, aiming to understand how these physiological responses relate to food preference behaviors. Specifically, we provided an in-depth analysis of how visual food stimuli influence cerebral hemodynamics, subjective evaluations, and implicit preferences. The experiment focused on the prefrontal cortex and parotid regions, examining neural responses to static and dynamic visual stimuli of ice cream in different melting states and colors. We analyzed neural activity in the left and right prefrontal cortices and parotid regions, as well as the relationship to response times (as measures of implicit preferences) in evaluating "liking" and "wanting." This approach enabled us to investigate the effects of visual stimuli on physiological responses and subjective evaluations through complex mechanisms involving the brain's reward system and appetite behaviors.

Our findings revealed that subjective evaluations varied significantly with the melting state and color of the ice cream stimuli. Notably, fresh, intact ice cream (State 1) received high ratings for both "liking" and "wanting," whereas melted ice cream (State 4) received significantly lower ratings. These results suggest that freshness and visual appeal are critical factors in stimulating appetite, emphasizing the importance of visual integrity in food presentation.

Physiological responses indicated that visual stimuli, both static and dynamic, significantly influenced hemodynamic responses in the parotid and prefrontal regions, with specific regional activations corresponding to "liking" and "wanting" evaluations. Static images elicited increased blood flow in the left prefrontal cortex and left parotid region during "liking" evaluations, suggesting that hedonic and reward processing is predominantly mediated by the left hemisphere. Conversely, dynamic video stimuli induced activation in the right prefrontal cortex and right parotid region, indicating that motivational processes related to "wanting" are more prominent in the right hemisphere. The contrast between static and dynamic stimuli revealed differential brain responses, with videos necessitating complex sensory integration and cognitive processing, leading to distinct hemodynamic patterns. These findings elucidate mechanisms by which visual stimuli affect physiological responses and behavior through both conscious and unconscious processes.

We observed significant correlations between subjective evaluations and physiological indicators. Specifically, differential correlations were identified between changes in parotid blood flow and "liking" and "wanting" evaluations across hemispheres. Furthermore, a negative correlation between reaction times and selection frequency was found, indicating that shorter reaction times were associated with more frequent selections. This suggests that intuitive preferences influence decision-making speed.

Additionally, we observed a trend in the relationship between subjective evaluations (explicit evaluations) and reaction times (implicit preferences), wherein shorter reaction times (indicating stronger implicit preferences) generally corresponded to higher subjective evaluations. This finding highlights a connection between explicit "liking" and "wanting" evaluations and unconscious response speeds. A significant correlation was also found between reaction times and physiological indicators, with shorter reaction times associated with changes in parotid and prefrontal cortex activity. These results suggest that implicit preferences may influence appetite behaviors via physiological responses.

In conclusion, visual food stimuli influence appetite behaviors through physiological responses, subjective evaluations (explicit measures), and reaction times (implicit preferences). Utilizing fNIRS to measure brain activity, our study demonstrated that visual food stimuli (S) elicit specific physiological responses (O) that closely correlate with subjective evaluations (R), thereby providing critical empirical evidence supporting the theoretical framework of the S-O-R model. These findings offer valuable insights into how visual food cues impact physiological responses and behavioral intentions. Specifically, we confirmed that visual ice cream stimuli triggered parotid blood flow changes associated with subjective evaluations of "liking" and "wanting."

Keywords: Visual food stimuli, Appetite-related behavior, Metabolic responses, fNIRS indicators, Stimulus-Organism-Response (SOR) model, Biological food preference task

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Chapter 1

Introduction

1.1 Topic and Motivation

The visual appearance of food is a powerful determinant of human eating behavior, appetite, and subjective experiences such as "liking" and "wanting." Research has shown that color, shape, and the physical state of foods can alter perceived freshness, nutrient content, and overall palatability, thus influencing individuals' consumption choices. These influences are far from trivial: heightened attractiveness of a food's appearance can increase consumption, whereas visual signs of deterioration (e.g., melting or deformation) can discourage intake. Although many studies rely on static images to investigate these effects, real-life eating contexts often involve dynamic cues—foods change over time, and motion-rich stimuli such as videos can be more potent triggers for appetite than static images.

The influence of visual changes in foods on appetite and eating behavior has been identified as a multifaceted and significant research topic. Among such foods, ice cream, whose external appearance changes distinctly with temperature and the passage of time, provides a readily observable "deterioration process" (i.e., the transition from a solid to a melting state). This visual transformation is thought to exert a considerable impact on physiological and psychological responses, potentially either enhancing or diminishing appetite. On the other hand, for older adults or individuals with reduced swallowing function, the transition of foods from a solid to a semisolid or liquid form is not necessarily negative. Indeed, the shift to a softer consistency may improve ease of ingestion and mouthfeel, thereby promoting both food intake and salivary secretion. However, many questions remain regarding how such visual and physical transformations of foods influence appetite and salivary secretion in actual practice.

In this study, the deliberate presentation of melting ice cream is employed to investigate how this deterioration process affects physiological responses (e.g., salivary secretion) and the consumer's psychological reactions. Clarifying the interactions between subjective evaluations of "taste" and "freshness" related to visual changes, and the corresponding physiological responses, is an essential approach to comprehensively understand how visual modifications in foods alter eating behavior. The findings hold the potential to be applied to the development of more effective nutritional management strategies and the proposal of food forms suited to older adults or individuals with specific dietary restrictions.

Despite growing evidence that such visual cues modulate physiological responses (e.g., salivary secretion, heart rate) and reward-related brain activity (e.g., in the prefrontal cortex), several key research gaps persist. For example, it remains unclear how dynamic food stimuli (e.g., videos showing ice cream melting) might generate stronger or more nuanced physiological and neural responses compared to static food images. In addition, questions about the lateralization of "liking" and "wanting" in the left and right hemispheres—and how these processes interact with salivation—have yet to be fully addressed. Lastly, because appetite research often relies heavily on subjective questionnaires, there is a need to incorporate more objective physiological measures (e.g., functional near-infrared spectroscopy, or fNIRS) to achieve a more comprehensive and reliable assessment of human eating behavior.

Understanding how visual food cues operate, especially under dynamic conditions, holds promise for both theoretical advances and practical applications. Insights may inform healthier product design, tailored nutritional strategies, and interventions for specific populations (e.g., older adults or individuals with dysphagia), for whom visual and physical transformations of foods can be pivotal in determining intake and overall satisfaction.

1.2 Research Questions and Unresolved Problems

Building on the motivation described above, this dissertation seeks to address several unresolved issues:

Firstly, although static images of food have yielded important findings, the comparative impact of dynamic visual cues on appetite, "liking," and "wanting" is not well understood. How might the presentation of time-evolving food (e.g., melting ice cream) elicit different neural and physiological responses compared to static images? Numerous studies have examined static food images, the influence of dynamic visual stimuli, such as food-related videos, on physiological and neural responses remains insufficiently explored. Dynamic stimuli, by presenting more realistic and temporally evolving visual information, may exert a stronger influence on appetite, "liking," and "wanting" compared to static stimuli. Comparative research between these modalities is essential to deepen our understanding of their differential impacts.

Secondly, When food undergoes visual transformations, such as melting or deterioration, how does this change in appearance affect subjective evaluations ("liking," "wanting"), physiological responses (e.g., salivary secretion), and neural activity in the prefrontal cortex and parotid gland regions? Are these transformations uniformly negative in terms of appetite, or might they sometimes be beneficial? Changes in the physical state of food, such as freshness or melting, are visually salient and may significantly influence visual attractiveness, eating motivation, and physiological responses. However, the effects of these temporal transformations on subjective evaluations and neural activity remain underexamined. Exploring these changes can elucidate how dynamic visual properties of food impact human behavior and perception.

Thirdly, the role of the left and right prefrontal cortex and parotid gland regions in mediating "liking" and "wanting" remains unclear. Specifically, the relationship between these neural structures and physiological responses, such as salivary secretion, lacks definitive conclusions. What role do the left and right prefrontal cortex and parotid gland areas play in these processes? Investigating hemispheric functional asymmetry in these regions could provide insights into how brain activity differentially contributes to subjective and physiological responses to food stimuli.

Finally, despite its widespread utility in understanding stimulus-response mechanisms, empirical studies utilizing the Stimulus-Organism-Response (S-O-R) model are limited in the context of visual food stimuli and their relationship with physiological responses and behavioral intentions. This model postulates that a stimulus (S) triggers an organismic internal state (O), leading to a response (R). Applying this model to examine how visual food stimuli influence physiological responses and behavioral intentions can offer a robust framework for understanding these complex interactions. How can we best combine objective biometrics (e.g., fNIRS) with subjective evaluations to gain a holistic picture of eating behavior?

1.3 Research objectives and Approach

1.3.1 Research objectives

This study uses both static images (static stimuli) and dynamic videos (dynamic stimuli) of ice cream to investigate how different forms of visual food stimuli influence prefrontal cortex and parotid gland activity, subjective evaluations, and reaction times. By comparing static versus dynamic presentations, we seek to illuminate the temporal and spatial changes in brain activity related to "liking" and "wanting," as well as the role of dynamic stimuli in modulating these responses.

A major focus is on the melting state of ice cream. By varying the degree of melting, we can observe how changes in visual appearance affect subjective pleasure ("liking"), motivational drive ("wanting"), and physiological markers such as salivary secretion. This approach allows us to explore the intersection of food freshness, visual appeal, and the neural processes underlying eating behavior.

Another core objective is to capture and map brain activity using functional near-infrared spectroscopy (fNIRS). This method helps us explore how left–right prefrontal cortex activity aligns with participants' evaluations of "liking" and "wanting." Furthermore, we examine parotid gland responses—which can serve as a proxy for physiological appetite cues—in conjunction with fNIRS signals to investigate how emotional and cognitive processing links to appetite regulation.

Additionally, the functional asymmetry of left–right hemispheres is of special interest. By analyzing differences in prefrontal cortex and parotid gland activation, we hope to clarify how each hemisphere contributes to "liking," "wanting," and other physiological reactions to appetitive cues.

Finally, to ensure our findings are robust and generalizable, individual differences are carefully considered throughout this research. Variables such as personal food preferences, hunger levels, cultural background, and eating habits are recorded and controlled as needed. This holistic approach aims to mitigate the influence of participant variability and strengthen the broader applicability of our results.

1.3.2 Methodological Framework

To address these research objectives, we employ a mixed-methods approach combining psychophysiological and neuroimaging techniques. The following key components guide our methodology.

Use of Static and Dynamic Stimuli: We systematically present ice cream stimuli in multiple melting states through both static images and dynamic videos. This design allows us to isolate how motion and temporal information modulate cognitive, emotional, and physiological responses—crucial factors that static images alone may not fully capture. Ice cream serves as an ideal food model due to its highly visible degradation process (melting) and its strong visual appeal or aversion when semi-melted.

Functional Near-Infrared Spectroscopy (fNIRS): We use fNIRS to measure neural activity in the prefrontal cortex and parotid gland regions while participants view and rate the ice cream stimuli. By tracking hemodynamic responses, we can map how "liking" and "wanting" responses are represented in real time. Our analysis further focuses on left–right asymmetries, offering insight into functional differences between hemispheres in response to evolving visual food cues.

Salivary Secretion as a Physiological Marker: Concurrently, we measure parotid gland activity to capture changes in salivary secretion. This provides an objective physiological marker linked to appetite and allows us to investigate whether cognitive-emotional responses (as indicated by fNIRS) align with physiological indices of hunger or craving. By correlating neural and salivary data, we can better understand how subjective experiences translate into physical signals of appetite.

Subjective Questionnaires and Individual Differences: Alongside these objective measures, we administer subjective questionnaires to gauge participants' "liking," "wanting," overall appetite, and perceived food freshness. Demographic and lifestyle data—such as cultural background, hunger levels, and eating habits—are also collected. This multi-dimensional dataset lets us address individual variations that might influence both neural responses and appetite-related behaviors.

By integrating both objective (fNIRS, salivary secretion) and subjective assessments, as well as carefully controlling the properties of the ice cream stimuli (static vs. dynamic, varying melting states), our study aims to capture a comprehensive, nuanced picture of how visual cues can modulate eating behavior. This dual focus on measurable physiology and personal experience ensures that our findings speak to both the mechanistic underpinnings of appetite and the variability of real-world eating contexts.

1.4 Significance, Benefits, and Expected Contributions

This research contributes to the understanding of how dynamic visual cues shape human eating behavior from both theoretical and applied perspectives:

1.4.1 Social and Practical Impact

Nutritional Management and Food Design:

By investigating how dynamic presentations of food (e.g., videos of ice cream melting) affect both neural and physiological markers of appetite, this study provides foundational insights for creating healthier and more appealing food products. In particular, it sheds light on how the visual presentation of foods can either preserve or enhance appetite, even as the food transitions from a solid to a softer state.

Older Adults and Individuals with Swallowing Difficulties: For populations with specific dietary needs, the melting process may facilitate swallowing and improve mouthfeel. However, visual appeal also matters. The findings can inform strategies that ensure foods remain enticing despite modifications in texture, ultimately supporting better nutritional intake.

General Consumers: From a product development standpoint, understanding the factors that make foods look "fresh" or "attractive" (e.g., color, shape, state of semi-melt) can guide everything from packaging design to advertising. By merging these insights with knowledge of neural processing, manufacturers could innovate healthier snack or dessert alternatives that retain a high level of visual allure.

Public Health Interventions:

Given that visual cues strongly shape appetite, this research can inform public health strategies aimed at both promoting healthy eating and mitigating overconsumption.

Promote Healthier Eating Habits: Campaigns might capitalize on appealing visuals of fruits, vegetables, or nutrient-dense meals to stimulate appetite for healthier options.

Curb Overconsumption: Conversely, understanding which visual triggers most strongly prompt cravings can help individuals and health agencies moderate exposure to tempting visuals, supporting better portion control and dietary adherence.

These social and practical implications underscore the tangible ways in which experimental findings on food visuals can translate into improved eating behaviors and dietary outcomes across diverse demographic groups.

1.4.2 Academic and Theoretical Advancements

Neurophysiological Basis of "Liking" and "Wanting":

Traditionally, "liking" (the pleasurable aspect of eating) and "wanting" (the motivational drive to pursue food) have been treated as overlapping constructs. By examining brain activity through functional near-infrared spectroscopy (fNIRS) in tandem with salivary gland responses, this research differentiates the two reward components more effectively. The deliberate inclusion of dynamic stimuli (like melting ice cream) allows us to see how "liking" and "wanting" fluctuate in real time, potentially highlighting functional asymmetries in the brain's left and right hemispheres—particularly in regions associated with approach and avoidance behaviors.

Refinement of the S-O-R Model:

The Stimulus–Organism–Response (S-O-R) framework has long been used to understand how external cues trigger internal states that lead to certain behaviors. By incorporating objective neurophysiological measurements (e.g., brain hemodynamics, salivary secretion) with subjective self-reports (e.g., taste perception, feelings of "freshness"), this dissertation provides a more comprehensive version of the S-O-R model.

Specifically, the incorporation of objective measures, such as real-time neural activity and physiological data, provides a robust, empirically grounded perspective on the internal processing of visual food cues. By moving beyond purely subjective evaluations, this approach reveals the underlying mechanisms through which dynamic visual stimuli are interpreted and translated into appetite-related responses.

Furthermore, the development of a comprehensive framework, integrating physiological measurements, neuroscience insights, and subjective self-reports, enables a more nuanced and multidimensional understanding of eating behavior. This integrated methodology offers valuable insights into how specific visual stimuli, such as the melting of ice cream, influence both the cognitive and emotional dimensions of food perception. Together, these advancements contribute to a holistic view of how visual cues modulate human consumption patterns, bridging the gap between subjective experiences and objective biological processes.

Such an enhanced model can serve as a data-driven foundation for future explorations into the interplay between visual stimuli, neural processing, and human consumption patterns.

1.4.3 Value for Society:

Healthier Eating Choices: By pinpointing how even subtle changes in the appearance of food can significantly shape appetite, this research can encourage more mindful food environments. For restaurants, cafeterias, or home kitchens, insights into the role of color, texture, and melting states can direct the design of meals that are both visually engaging and nutritionally balanced. Specifically, effective use of visual cues can help institutions (e.g., hospitals, schools) align food offerings with healthy dietary goals, using presentation strategies to enhance the appeal of nutrient-rich foods and discourage overindulgence in calorie-dense items.

Improved Quality of Life: For populations dealing with specific dietary requirements—such as older adults, people recovering from surgery, or those with certain chronic conditions—this work highlights the dual importance of practical consistency (softer or liquid forms) and visual appeal in sustaining adequate nutrition.

Accommodating Special Needs: Foods that naturally transition to a softer state, like melting ice cream, may help individuals maintain sufficient caloric and fluid intake without sacrificing the sensory enjoyment of eating.

Practical Guidelines: Healthcare providers, caregivers, and family members can apply these insights to reduce feeding difficulties, potentially preventing complications such as unintended weight loss or aspiration pneumonia in vulnerable individuals.

By emphasizing how visual aspects of food can positively influence eating decisions, the research paves the way for real-world improvements in public health and individual well-being—particularly within communities that depend on specialized nutritional support.

1.5 Previous Research

1.5.1 Influence of Visual Characteristics on Appetite and Eating Behavior

The visual appearance of foods significantly influences individuals' food choices and appetite. Sensory cues such as color, shape, and the physical state of food are closely associated with its perceived nutrient content, energy value, and the elicitation of pleasant or unpleasant sensations. Among these cues, visual stimulation is a crucial regulator of appetite, as it enables individuals to predict food characteristics and influences eating behavior [1, 2]. For instance, when subjects are presented with visual food stimuli, significant differences in blood flow in the parotid region have been observed between groups with low and high appetite ratings [3]. This observation underscores the interplay between visual cues and physiological responses, particularly salivation, in modulating appetite. People can predict food characteristics through photos and videos, and this visual information influences eating behavior. The chemical senses—sight, smell, and taste—are key factors affecting appetite, food choice, and intake [4].

Research has extensively investigated how the visual characteristics of food, such as color, shape, and state, impact human appetite and eating behavior. Visual stimuli from food play a significant role in stimulating preferences and appetitive responses, thereby encouraging food intake [1]. Visual elements like color, shape, and physical state interact with sensory perceptions such as taste and smell, contributing to the overall eating experience [2]. The appearance of food influences perceptions of freshness and quality; visually appealing and fresh-looking food enhances appetite [5], whereas alterations in the food's physical state, such as melting or deformation, can reduce palatability and the desire to eat.

Color plays a pivotal role in taste perception and appetite. Previous studies have established that warm colors like red and orange tend to enhance sweetness perception [2]. Color also aids in assessing freshness and quality, with vibrant hues typically evoking perceptions of freshness and appealing to consumers, thereby enhancing a food's attractiveness. The shape and presentation of food contribute to its visual appeal and affect eating behaviors. For instance, visually appealing food presentations have been shown to increase consumption in children by promoting interest and anticipation [6]. Additionally, food freshness and physical state significantly influence visual appeal, affecting preferences and appetite. Arrangements evoking emotions, like a smiling or sad face, trigger distinct emotional responses in the brain's emotion-processing areas, impacting appetite [7]. Appearance also activates reward-related brain areas like the amygdala and ventral striatum, which stimulate appetite [8]. The sensory appeal of texture and appearance complements broader sensory experiences, including taste and aroma, playing an essential role in shaping eating habits and promoting healthier eating behaviors [9].

These studies suggest that physical degradation, such as melting or breaking, can reduce palatability, leading to a decline in appetite due to diminished visual appeal. Although significant findings have emerged regarding the influence of visual food stimuli on eating behaviors, several key challenges and unresolved issues remain. Notably, most current research utilizes static food images, leaving a gap in understanding the effects of dynamic visual stimuli—such as videos showing food undergoing physical changes—on visual appeal and appetite. This highlights the need to examine how dynamic changes in food state impact cognitive, emotional, and physiological responses. Specifically, food items undergo physical transformations, such as deterioration or melting, which may influence both their visual attractiveness and subsequent eating behaviors. Further investigation is needed to clarify how dynamically altered food images affect subjective evaluations and brain activity. For instance, Goldberg et al., found that dynamic changes in food state may impact cognitive, emotional, and physiological responses differently than static images [10].

Future research should address the complexity of cognitive processing in response to dynamic stimuli and their potential interactions with brain reward systems and regions associated with appetite. Another area requiring further investigation is the role of individual differences. Responses to colors, shapes, and state changes of food can vary based on personal preferences and cultural backgrounds, yet research considering these individual differences is limited. Therefore, studies involving diverse participant samples are essential for drawing more generalizable conclusions.

1.5.2 Role of Saliva in Appetite Regulation

Saliva is recognized to have a variety of functions, which plays a crucial role in both oral and systemic health. Saliva secretion depends on a complex set of factors, including food-related cues, health status, and gender [11, 12]. Salivary glands are under the dual control of sympathetic and parasympathetic nerves, and different glands produce saliva with distinct characteristics. Sympathetic nervous system activity causes the parotid gland to secrete serous, $\aleph$-amylase-rich saliva, while parasympathetic activity prompts the submandibular and sublingual glands to produce viscoelastic, mucin-rich saliva [13–15]. Each component of saliva is regulated to perform specific functions.

Sensory food cues, such as appearance, fragrance, and taste, can induce rapid saliva secretion in the oral cavity, known as the cephalic phase salivary response [16–19]. This response includes physiological reactions to food-related cues such as the thought, fragrance, appearance, and taste of food [20]. Many studies have shown that sensory exposure to various foods increases saliva production, linking sensory cues directly to physiological responses that influence appetite [21, 22]. Pavlov's classic conditioning experiments highlighted this relationship, establishing an association between visual cues and physiological responses [23].

1.5.3 Visual Stimuli and Physiological Responses

Visual food stimuli can trigger physiological changes beyond salivation, such as fluctuations in heart rate and skin conductance, indicating activation of the autonomic nervous system [21]. For instance, Nederkoorn et al., found that viewing images of food increases saliva production, contributing to heightened appetite. Moreover, increases in heart rate and alterations in skin conductance suggest that visual food stimuli influence both the sympathetic and parasympathetic nervous systems. Additionally, neuroimaging studies have shown that visual food stimuli activate the brain's reward system. Killgore and Yurgelun-Todd reported that presenting food images stimulated reward-related regions, such as the amygdala and prefrontal cortex [24]. These neural activations are believed to interact with physiological responses, promoting appetite and potentially influencing eating behavior.

However, challenges remain regarding the relationship between visual food stimuli and physiological responses, including individual differences, the diversity of stimulus characteristics and responses, as well as the long-term and health-related impacts. First, physiological responses to visual stimuli may vary depending on individual dietary habits, cultural background, and nutritional status [25]. Research that accounts for these individual differences is currently limited, and further examination is needed to assess the generalizability of physiological responses. Additionally, the specific characteristics of visual stimuli, such as color, shape, and whether the stimulus is dynamic or static, are not fully understood in terms of their impact on physiological responses. In particular, there is limited research on the differences in physiological responses elicited by dynamic video stimuli compared to static images [26].

Moreover, while visual food stimuli have been shown to influence eating behavior through physiological responses, it remains unclear how these effects contribute to long-term health outcomes and dietary habits. To clarify the potential links between visual food stimuli and conditions such as obesity and eating disorders, further longitudinal studies are needed [27].

1.5.4 Limitations of Subjective Appetite Assessments

Traditional methods for assessing appetite have predominantly relied on subjective assessment methods, such as questionnaires or interviews, which require cognitive information processing and are influenced by factors like social desirability [28], and have several noted limitations. Subjective evaluations are heavily influenced by participants' perceptions, emotions, and social desirability bias, leading to challenges in accuracy and reproducibility. Responses to the same question may vary from day to day, compromising data consistency.

Additionally, self-assessments are often subject to unconscious biases—such as anchoring bias and social desirability bias—which can result in reported outcomes that differ from the individual's actual appetite state. If participants are unable to accurately perceive their own hunger levels or misunderstand questionnaire items, the precision of the assessment diminishes further. Moreover, implicit motivation is difficult to measure, as humans make various daily food decisions that involve motivational processes we may be unaware of, cannot articulate, or do not wish to disclose [28, 29]. People's choices and actions regarding food and food cues involve complex cognitive, sensory, and emotional processes, especially in the current food-abundant obesogenic environment [30].

These issues make it difficult to achieve objective and quantitative evaluations of appetite. In clinical settings and research, the accuracy of appetite assessments directly impacts the measurement of treatment or intervention efficacy, necessitating improvements in data reliability. Murray and Rees highlighted this problem using itch assessment as an example. They pointed out that subjective evaluations do not always align with objective behavioral measurements—such as recording scratching behavior using actigraphy. They attributed this discrepancy to questionnaires being susceptible to anchoring bias, where participants adjust their responses based on past experiences or environmental factors. They emphasized the need for caution when using subjective evaluations [31].

Similarly, Barone et al. discussed methods for measuring body composition, noting that results obtained from different assessment techniques can vary depending on statistical methods and participant characteristics (age, gender, medical conditions). They argued that subjective self-evaluations could negatively impact measurement accuracy due to these factors [32]. Additionally, Taylor compared students' self-evaluations with multifaceted feedback assessments, demonstrating that self-evaluations are prone to overestimation and bias [33].

From these studies, it is evident that subjective methods in appetite assessment are susceptible to psychological and emotional influences, indicating limitations in reliability. Therefore, there is a pressing need to develop evaluation methods that combine objective indicators and automated technologies. Such approaches would enhance the accuracy and reliability of appetite assessments, which is crucial in clinical practice and research where precise measurement directly influences the effectiveness of treatments and interventions.

1.5.5 Need for Objective and Subjective Measurements

Given the limitations of subjective assessments, recent years have seen technological advances in biometric systems that measure psychophysiological parameters, making it possible to examine implicit processes involved in food intake [34]. Biometrics, as non-invasive behavioral and physiological measures, can reflect motivation and emotional responses to food, identifying individual characteristics based on biological and physiological properties, and are commonly used in food science and consumer science [35]. However, the limited number of studies on biometrics and inconsistent results make it difficult to compare study outcomes, highlighting the need to combine biometric measures with traditional measures of appetite. Investigating individual motivations and responses behind food choices and intake is essential to promote healthier eating habits. Combining objective biometric data with subjective evaluations can provide a more comprehensive understanding of appetite behaviors and the factors influencing food choice. This approach addresses the limitations of subjective methods by incorporating physiological measures that are less susceptible to biases and can capture unconscious processes.

1.5.6 Discussion of Objective Evidence (Reliability and Validity) and Subjective Data

Generally, objective measurements are considered superior to subjective measurements because they reduce errors resulting from human perception or judgment by utilizing measuring instruments. Objective measurements, such as physiological responses recorded by devices, provide quantifiable data and a standardized approach [36]. Conversely, subjective measurements, such as survey questionnaires and sensory evaluations, rely on individual perceptions and sensations, which can introduce substantial errors due to biases and variability [36].

However, this perspective is not universally accepted, especially in fields like medicine. For example, functional near-infrared spectroscopy (fNIRS), a tool for measuring brain function, has been criticized for high noise levels relative to the signal, instability, and challenges in accurately determining the origin of measured signals [37]. Issues such as the mixing of skin blood flow changes due to probes being placed directly on the skin complicate the validity of fNIRS results. Therefore, the reliability of fNIRS measurements might be lower than generally assumed, necessitating careful consideration of results based on cognitive scientific opinions rather than accepting them at face value.

In contrast, psychometric methods that quantitatively analyze human cognition using established psychological scales, even without instruments, are considered to have higher reliability and validity than some brain function measurements. Psychometric measurements can gather data from many participants and obtain statistically significant results, providing valuable insights into conscious emotional processes [38].

Both objective and subjective measurements serve important purposes in research on the Stimulus-Organism-Response (S-O-R) model in the sensibility evaluation of the environment [39–42]. Objective measurements, such as physiological responses, allow researchers to quantify and assess conscious and unconscious emotional processes [43]. Subjective measurements capture individual perceptions and experiences, reflecting an individual's interpretation of the environment. Therefore, it is not a matter of superiority but rather of using the appropriate measure based on the research objective and the level of analysis required [44].

Objective measurements can be useful as they may show a high correlation with subjective measurements, providing a standardized approach to assessing emotional experiences. However, subjective measurements are valuable for understanding personal interpretations and experiences. Both objective and subjective factors should be considered in future research to better understand how the environment affects an individual's perception and behavior.

1.5.7 The Stimulus-Organism-Response Model and Biometric Measurements

The Stimulus-Organism-Response (S-O-R) model is a theoretical framework that explains how environmental stimuli influence behavioral responses through an individual's internal state or organismic response [45]. Widely used in marketing and consumer behavior research, this model helps analyze the impact of store environments on consumers' emotions and purchasing intentions. The model consists of three elements: external stimuli (Stimulus), the organism's internal processes (Organism), and the resulting responses (Response). The stimulus refers to external factors influencing perception and behavior, which can include various elements such as media richness, live streamer attractiveness, and environmental corporate social responsibility (CSR) [43, 46, 47]. The organism represents internal factors like cognitive processes, emotions, and motivations influenced by the stimulus. The response is the behavioral or psychological outcome in reaction to the stimulus and organism, including behaviors such as visit intention, impulse buying, and purchase intention [48, 49].

Advances in biometric technology have made it possible to objectively assess organismic responses within the S-O-R model. Functional near-infrared spectroscopy (fNIRS), a non-invasive method of measuring brain activity, has gained attention as a tool for capturing consumers' subconscious responses in real-world settings [50]. Studies using fNIRS have shown that prefrontal cortex activity in response to visual stimuli is associated with emotional evaluation and decision-making processes [51]. Furthermore, there is growing research examining the link between brain activity measured by fNIRS and subjective preferences and desires.

The S-O-R model has been applied across diverse contexts, including tourism, payment systems, online marketplaces, and the food service industry. For instance, Jeong et al. [43] employed the S-O-R model to examine the effect of personalized recommendation stimuli on customers' response rates in the context of Home Meal Replacement products. In tourism, the model has been used to explore motivators influencing tourists' behaviors and intentions [46, 52]. Dinanti and Bharata applied the S-O-R model to study the adoption of peer-to-peer mobile payment systems, identifying key success factors and drivers of user intention [53]. The model has also been utilized to analyze factors influencing purchase intention in online marketplaces, including store atmosphere and online customer reviews [54]. Additionally, Kini et al. [49] investigated the acceptance of location-based advertising using the S-O-R model, with relevance and context playing significant roles.

However, challenges remain in combining the S-O-R model with biometric measurements. Interpreting organismic responses from biometric data is complex due to their multidimensional nature. While fNIRS allows for brain activity measurement, it has limitations in spatial resolution and the brain regions it can assess, making it difficult to capture organismic responses comprehensively [37]. To clarify the relationship between physiological responses and subjective emotions or behaviors, studies combining multiple biometric indicators are needed. Applying the S-O-R model requires controlling for or considering multiple factors. Although theoretically valuable, the S-O-R model requires refinement to accurately predict real consumer behavior. More empirical research is essential to understand the extent, magnitude, and persistence of the effects of organismic responses on behavior [55].

1.5.8 "Liking" and "Wanting" in Eating Behavior

In the field of behavioral neuroscience, "liking" and "wanting" are considered critical elements of eating behavior, each associated with distinct neural foundations [56]. Berridge and Robinson proposed that within the reward system, "liking" and "wanting" are mediated by separate neural mechanisms. "Liking" refers to the subjective pleasure or satisfaction experienced during food consumption and involves neurotransmitter systems such as the opioid and gamma-aminobutyric acid (GABA) systems [57]. In contrast, "wanting" is associated with the motivation or desire to seek out food and engage in reward-seeking behaviors, with the dopaminergic system playing a central role [58]. Activation of the dopaminergic system enhances "wanting" and can lead to excessive pursuit of food or substances, though this does not necessarily increase subjective pleasure ("liking") [59]. Recent studies using functional near-infrared spectroscopy (fNIRS) have aimed to capture these concepts by examining differences in brain activity associated with "liking" and "wanting," exploring how these distinct processes manifest in neural responses.

1.5.9 Functional Asymmetry in the Brain's Hemispheres

The left and right hemispheres of the brain display functional asymmetry in the regulation of emotions and behavior. Davidson proposed that the left prefrontal cortex is associated with positive emotions and approach behavior, while the right prefrontal cortex is linked to negative emotions and avoidance behavior [60, 61]. In terms of the association between "liking" and the left hemisphere, Davidson suggested that increased activity in the left prefrontal cortex correlates with positive emotional states, such as happiness and pleasure, as well as approach behaviors directed toward rewards [62]. Supporting this, Small et al. reported that the experience of pleasure during food intake strongly activates regions within the left hemisphere, including the prefrontal cortex and insular cortex, which are involved in processing food rewards [63].

In contrast, regarding "wanting" and the right hemisphere, activity in the right prefrontal cortex is associated with negative emotions, such as anxiety and fear, and avoidance behaviors. However, the direct link between this activity and "wanting" remains unclear. According to Corbetta and Shulman, the right hemisphere may play a role in the allocation of attentional resources and motivation [64]. Nevertheless, the direct correspondence between "liking" and "wanting" and hemispheric activity is not consistently supported across studies. For instance, Georgiadis et al., using fMRI, found that left prefrontal cortex activity was associated with pleasurable experiences, particularly in response to sexual stimuli [65]. Rolls noted that the orbitofrontal cortex (OFC), which is present in both hemispheres, is crucial in processing food rewards, but he remarked that any functional asymmetry within the OFC remains unclear [66].

Functional near-infrared spectroscopy (fNIRS) is widely employed as a method for measuring brain activity due to its simplicity and safety. However, it has limitations in spatial resolution, making it challenging to directly measure the activity of deep brain regions such as the limbic system and basal ganglia [37]. This constraint hinders the detailed elucidation of deep reward system responses to food stimuli, thereby imposing limitations on the interpretation of brain activity. Moreover, the neural mechanisms by which visual food stimuli activate the brain's reward systems and appetite-related regions, leading to subsequent behaviors, remain insufficiently understood. Specifically, while differences in the neural substrates of "liking" and "wanting" have been suggested [56], it is not yet clear how visual food stimuli affect these components. Furthermore, our understanding of how functional asymmetries in the left and right prefrontal cortex and parietal regions influence responses to visual food stimuli is still limited. Davidson's research indicates that the left prefrontal cortex is associated with positive emotions and approach behaviors, whereas the right prefrontal cortex is related to negative emotions and avoidance behaviors [60]. However, the implications of these findings for appetite and eating behaviors have not been fully elucidated.

Challenges also exist regarding individual differences and their relationship with subjective evaluations. Brain activity in response to food stimuli is influenced by personal preferences, cultural background, hunger state, and other factors [67]. To control for these individual differences and generalize the relationship between subjective evaluations (”liking” and ”wanting”) and brain activity, studies involving larger and more diverse participant samples are necessary. In addition, concerning dynamic stimuli and temporal resolution, many studies employ static images of food, despite the importance of dynamic visual information in real eating environments. Research leveraging the temporal resolution of fNIRS to analyze temporal changes in brain activity in response to dynamic food stimuli is still limited. Clarifying how dynamic stimuli affect evaluations of ”liking” and ”wanting,” as well as brain activity, is a pressing need. Finally, while the multi-channel capabilities of fNIRS devices have made it possible to simultaneously measure activity across extensive brain regions, data analysis has become more complex [68]. Establishing reliable data analysis methods—including artifact removal and standardization of statistical analysis techniques—is essential.

1.5.10 Effects of Static and Dynamic Visual Stimuli on Brain Activity

Previous studies have demonstrated that static images and dynamic videos exert different influences on brain information processing. Dynamic stimuli, which encompass temporal and spatial information, require more complex cognitive processing and promote activation across widespread brain regions [69]. Notably, dynamic visual stimuli tend to capture attention more effectively and induce stronger emotional responses compared to static images. Several studies have reported that dynamic food videos may have a stronger appetite-inducing effect than static images. Nummenmaa et al. showed that dynamic food videos, compared to static images, more strongly elicit visual attention and activate reward-related brain regions such as the amygdala, striatum, and hypothalamus [70]. This suggests that dynamic stimuli may more robustly evoke appetite and influence eating behavior. Elder and Krishna reported that dynamic food advertisements enhance consumers' emotional responses and increase purchase intentions [71]. Their findings indicate that moving visual stimuli can augment product attractiveness and affect consumer attitudes and behaviors. Similarly, Siep et al. found that dynamic food videos increase activity in emotion and reward-related regions, including the prefrontal cortex and insula, more than static images [72]. Activation in these regions is associated with desire and craving for food.

Conversely, numerous studies have focused on static food images, which capture a single moment in time. Killgore and Yurgelun-Todd reported that static images of high-calorie foods increase activity in the prefrontal cortex and amygdala, influencing appetite and eating behavior [24]. Toepel et al. demonstrated that the visual features of static food images—such as color, brightness, and contrast—affect activity in the visual cortex and reward-related regions [73]. Visually appealing foods were associated with stronger brain activity and higher hedonic evaluations. Studies directly comparing the effects of dynamic and static visual stimuli have highlighted the differences between them. Van der Laan et al. used functional magnetic resonance imaging (fMRI) to compare brain activity in response to static and dynamic food videos [74]. They found that dynamic videos induce stronger activity not only in the visual cortex but also in reward-related regions such as the frontal eye fields and nucleus accumbens. This suggests that dynamic stimuli may be associated with stronger reward prediction.

Despite these findings, several unresolved issues remain. There is a lack of detailed analysis regarding how specific properties of dynamic stimuli (e.g., content of the video, motion speed, viewpoint) and qualities of static images (e.g., resolution, visual complexity) affect brain activity and behavioral responses. Experimental studies that control for these factors are needed to elucidate their specific impacts. A comprehensive understanding of the relationship between physiological responses induced by dynamic and static visual stimuli—such as heart rate, skin conductance, and saliva secretion—and subjective appetite and hedonic evaluations is necessary. Research that simultaneously measures multiple physiological indicators and examines their association with brain activity is required to deepen our understanding of these mechanisms.

1.6 Structure and Content of this doctoral dissertation

1.6.1 Introduction

This chapter introduces the critical role of visual food stimuli in modulating appetite and eating behaviors. It establishes a theoretical foundation by exploring how sensory cues and physiological responses shape one's experience of food—particularly when visual appearances change over time. The discussion incorporates the Stimulus-Organism-Response (S-O-R) framework to elucidate how external stimuli (e.g., melting ice cream) influence internal processes such as salivation, motivation ("wanting"), and pleasure ("liking"). Additionally, the chapter reviews the limitations of relying solely on subjective assessment methods, thereby highlighting the need to integrate functional near-infrared spectroscopy (fNIRS) as a non-invasive tool for monitoring real-time brain activity. The chapter concludes by framing the research objectives, emphasizing the necessity of investigating both dynamic and static food stimuli, the roles of the prefrontal cortex and parotid regions, and physiological markers like cerebral blood flow variations to yield a more comprehensive understanding of human eating behaviors.

1.6.2 NIRS and Brain Activity

Given that this study adopts a metabolic perspective utilizing functional near-infrared spectroscopy (fNIRS), this chapter provides an overview of how functional near-infrared spectroscopy (fNIRS) can be used to investigate human brain activity. Next, the chapter discusses methodological considerations for designing robust fNIRS experiments. The chapter then focuses on two critical anatomical regions relevant to food-related research: (1) the prefrontal cortex (PFC), which influences decision-making, emotional regulation, and responses to food cues; and (2) the parotid gland region, which governs saliva production and thus reflects a core physiological response to appetite stimulation. This section emphasizes how fNIRS can illuminate the dynamic interplay between cortical activity, salivary responses, and food cues.

1.6.3 Experimental Methodology

This chapter provides a comprehensive overview of the study's methodology and describes the methodological framework used to investigate how participants respond to static and dynamic ice cream stimuli, focusing on both explicit and implicit food preferences. It explains how healthy volunteers were recruited under defined inclusion criteria, how cerebral blood flow was measured in both prefrontal and parotid regions using specialized fNIRS devices, and how visual ice cream stimuli (photos and videos) were systematically presented and rated. This chapter highlights the rigorous design choices that underpin this dissertation's examination of ice cream stimuli. By balancing laboratory control with ecologically valid tasks, the approach captures how participants consciously and unconsciously respond to food cues. The use of both prefrontal- and parotid-targeted fNIRS adds depth to the research, providing insight into how cerebral and salivary processes intersect with subjective "liking," "wanting," and actual choice behaviors.

1.6.4 Data Analysis and Results

This chapter provides a comprehensive overview of the study's data analysis and results. This chapter elaborates on data preprocessing, statistical methods, and specific metrics used, such as reaction times, ratings of liking and wanting, and fNIRS signals. Furthermore, the chapter presents a detailed analysis of the findings, including correlations between visual food stimuli, subjective evaluations, and physiological responses.

1.6.5 Discussion

This chapter provides an in-depth interpretation of the results within the context of previous research, focusing on how visual stimuli influence both subjective and objective measures of appetite. It highlights the distinct roles of the left and right prefrontal cortices in mediating hedonic and motivational processes, linking these neural activities to "liking" and "wanting" evaluations. The chapter further underscores the utility of functional near-infrared spectroscopy (fNIRS) in advancing the Stimulus-Organism-Response (S-O-R) model and elucidating the neurophysiological mechanisms underlying appetite behavior.

1.6.6 Relationships Between Chapters

Chapter 1 (Introduction) establishes the key research question and theoretical framework, emphasizing the importance of visual food stimuli in shaping eating behaviors. It sets out how the Stimulus–Organism–Response (S-O-R) model and the integration of subjective and objective measures (e.g., fNIRS) can illuminate "liking," "wanting," and other aspects of appetite. This foundational chapter grounds the entire dissertation and justifies the need for advanced neuroimaging techniques to explore visual cues and appetite regulation.

Chapter 2 (NIRS and Brain Activity) builds on Chapter 1's conceptual groundwork by introducing functional near-infrared spectroscopy (fNIRS). It explains the method's value for measuring cortical (prefrontal) activity and physiological responses (e.g., salivary activity in the parotid region). This chapter provides the technical underpinnings for subsequent experimental choices, directly informing the design and implementation strategies outlined in Chapter 3.

Chapter 3 (Experimental Methodology) operationalizes the theories and methods introduced in Chapters 1 and 2. It details participant recruitment, explains the choice of static and dynamic ice cream stimuli, and demonstrates how fNIRS was used to assess both explicit (rating scales) and implicit (forced-choice) food preferences. By unifying conceptual and technical elements, this chapter ensures a robust and replicable data collection process.

Chapter 4 (Data Analysis and Results) presents how the collected data—guided by the fNIRS framework in Chapter 2 and the methodology in Chapter 3—was processed, analyzed, and interpreted. It examines correlations among neural activity, salivary responses, subjective evaluations, and reaction times. This chapter validates or refines the hypotheses introduced in Chapter 1, demonstrating how the experimental procedures from Chapter 3 yield meaningful empirical findings.

Chapter 5 (Discussion) connects the empirical insights of Chapter 4 with the theoretical foundation laid out in Chapter 1. It also integrates the technical considerations from Chapter 2, discussing what the results reveal about "liking" versus "wanting," brain hemispheric functions, and physiological indicators of appetite. This chapter identifies strengths, limitations, and potential applications of the research, thereby linking the dissertation's core findings back to its guiding framework.

Chapter 2

NIRS and Brain Activity

2.1 Functional Near-Infrared Spectroscopy (fNIRS) in Measuring Brain Activity

Functional near-infrared spectroscopy (fNIRS) is a non-invasive method for assessing brain activity by emitting near-infrared light into brain tissue and detecting changes in concentrations of oxygenated hemoglobin (HbO) and deoxygenated hemoglobin (HbR) [50]. Due to its portability and participant-friendly design, fNIRS can be used in settings that simulate real-world environments, making it well suited for observing brain responses to food stimuli in real time.

Previous studies have reported that the prefrontal cortex (PFC) exhibits activation patterns associated with reward and decision-making in response to food stimuli. For instance, Zhao et al. examined neural responses to visual food cues, reporting that PFC activity correlates with participants' hunger levels [75]. Subsequent studies have also revealed that PFC activity depends on food type and caloric density, suggesting that factors such as cognitive control, attention, and the specific properties of food (e.g., palatability, caloric content) can substantially shape neural responses and, consequently, eating behavior. Additionally, Dabkowska-Mika et al., using functional MRI (fMRI), demonstrated that high-calorie food images increased blood oxygen level-dependent (BOLD) signals in various brain regions, including the visual cortex and prefrontal cortex, highlighting heightened neural activity in response to food stimuli [76]. Furthermore, Pimpini et al. found that the reward value of food is represented in specific brain activity patterns and modulated by attentional processes, rather than by body mass index (BMI) [77]. In individuals with obesity, Poghosyan et al. [78] reported that individuals with obesity exhibit decreased activation in reward-related regions but increased activation in attention-related areas when viewing food images. These neural response profiles may predict the success of weight-loss programs and highlight the integral role of brain activity in both eating behavior and weight management. Collectively, these studies underscore the utility of fNIRS in measuring neural responses to food stimuli and provides valuable insights into how these responses connect with behavioral tendencies, cognitive processes, and physiological states.

2.2 Functional Near-Infrared Spectroscopy (fNIRS) and the Metabolic Perspective

2.2.1 Historical Foundations and Core Principles of fNIRS

The origins of functional near-infrared spectroscopy can be traced to pioneering work on the noninvasive assessment of tissue oxygenation using near-infrared light [79]. Jöbsis [79] demonstrated how alterations in transmitted light intensities, under varying oxygenation states, could be measured in animal models. Later advancements built on the principle of neurovascular coupling—namely, that increased neuronal firing initiates local vasodilation and thereby elevates cerebral blood flow [80, 81].

In essence, fNIRS exploits the distinct absorption characteristics of oxygenated hemoglobin (HbO) and deoxygenated hemoglobin (HbR) to track cortical hemodynamic changes that serve as proxies for neural activity. Compared to other neuroimaging methods, fNIRS offers notable advantages such as reduced cost, greater portability, and enhanced participant comfort. As a result, it has proven especially attractive for investigations spanning diverse populations and real-life contexts.

2.2.2 Neurometabolic Coupling and Hemodynamic Responses

Brain functions such as sensation, movement, memory, cognition, and volition rely on the electrical activity of neurons, which is fundamentally powered by adenosine triphosphate (ATP). ATP production depends on the metabolic breakdown of glucose in the presence of oxygen. The correlation between neuronal firing and metabolic demands is termed neurometabolic coupling, whereas the relationship between metabolic activity and upregulated cerebral blood flow is referred to as flow-metabolism coupling. Collectively, these processes constitute neurovascular coupling.

Multiple non-invasive modalities can measure different facets of this neurovascular coupling. Magnetoencephalography (MEG) and electroencephalography (EEG) capture primary signals linked directly to neural activity. By contrast, positron emission tomography (PET) and magnetic resonance spectroscopy (MRS) examine secondary signals reflecting metabolic changes (e.g., glucose and oxygen consumption). Functional magnetic resonance imaging (fMRI) and fNIRS monitor tertiary signals tied to changes in blood flow, volume, and oxygenation states. These hemodynamic parameters complement direct neural signals by revealing how the brain's microvasculature adapts to shifting metabolic demands.

2.2.3 fNIRS and the Measurement of Hemodynamic and Metabolic Dynamics

fNIRS is especially valuable for capturing localized hemodynamic changes that co-occur with neural activity. In practice, when a cortical region is engaged, an increase in oxygenated hemoglobin (HbO) and a concomitant, slight decrease in deoxygenated hemoglobin (HbR) reflect the vasodilatory response within intracortical arterioles. As local cerebral blood flow rises, the overall volume of hemoglobin in that region also increases, providing a clear indicator of elevated cerebral blood volume. By concurrently measuring HbO and HbR concentrations, fNIRS allows researchers to map these vasodynamic and metabolic processes in real time.

Despite these capabilities, one must remain vigilant regarding potential confounding factors. Physiological fluctuations (e.g., respiration, autonomic nervous system activity) and scalp-derived signals can introduce artifacts, complicating the interpretation of the measured hemodynamic response. Consequently, appropriate filtering, signal processing, and experimental design considerations are critical for isolating the brain-specific components of the signal and reducing extraneous interference.

2.2.4 Toward a Deeper Understanding of Brain Metabolism via fNIRS

By focusing on both oxygenated and deoxygenated hemoglobin, fNIRS elucidates the balance between oxygen supply and consumption within the cerebral cortex. It thus serves as a window into the broader metabolic processes that underlie neural activity. In line with neurometabolic coupling principles, areas of increased neuronal activity exhibit enhanced glucose utilization and elevated oxygen demand. fNIRS captures the downstream hemodynamic signatures of these events, offering a complementary perspective to technologies that directly measure electrical activity or metabolic substrates.

This integrative capability makes fNIRS particularly valuable in studies where portability, cost-effectiveness, or participant comfort are critical. For instance, it has been employed in clinical research on developmental populations, patients with limited mobility, or individuals in naturalistic settings where more cumbersome imaging modalities (such as fMRI) are not feasible. Ultimately, by simultaneously quantifying oxygenated and deoxygenated hemoglobin, fNIRS delivers insights into how local blood flow and metabolic needs align with—or deviate from—the broader framework of neurovascular coupling. Researchers can thereby unravel the dynamic interplay between neuronal activation, metabolic consumption, and vascular responses, contributing to a richer and more nuanced understanding of brain function.

2.2.5 Study design

Designing robust fNIRS studies requires careful consideration of theoretical and practical factors to ensure meaningful, reproducible outcomes. This encompasses defining the research question with clarity, selecting suitable tasks and stimuli, and standardizing measurement protocols to limit variability. The experimental environment should minimize external distractions, and instructions to participants must be carefully structured to prevent inadvertent confounds. By adhering to rigorous methodological standards, studies can achieve both internal validity—capturing the true neural responses of interest—and external validity—facilitating comparison and replication across diverse experimental contexts.

The sample size, inclusion and exclusion criteria

Determining an appropriate sample size is paramount for ensuring statistical power, representativeness, and the generalizability of fNIRS findings [82–84]. Underpowered studies risk producing unstable estimates of effect sizes and may fail to detect genuine neurophysiological differences. Well-defined inclusion and exclusion criteria enhance data integrity by controlling for head size variability, scalp-to-brain distance, and skin or hair properties that influence optode-skin contact and signal quality [85]. Furthermore, representing diverse demographic groups—encompassing variations in skin tone, hair type, and other phenotypic features—bolsters the ecological validity of the findings and reduces the risk of bias [86, 87].

Experimental design

In fNIRS experimentation, stimulus parameters and temporal structure critically influence neural response detection. Adjusting the duration of stimulation blocks, inter-trial intervals, and the nature of the task itself can modulate the amplitude and reliability of the hemodynamic response [88, 89].

Nonlinearities, habituation effects, and potential carryover influences from preceding stimuli require balanced stimulus designs and temporal offsets. Selecting an appropriate number of blocks, ensuring participants remain engaged, and mitigating fatigue effects further improve signal quality. By carefully structuring experiments, researchers can isolate the neural correlates of specific cognitive or motor processes.

Placement of optodes

Optode placement—the spatial arrangement of sources and detectors on the scalp—shapes both the sensitivity and specificity of fNIRS measurements. Aligning optodes with standardized brain atlases, individualized anatomical data, or photogrammetry-based registration enhances localization of cortical regions, ultimately improving the spatial resolution of hemodynamic mapping [90–92] . Attention to practical issues such as securing stable optode-skin contact through specialized optodes or hair clips, and accounting for variations in melanin levels, reduces signal attenuation [82, 85]. Moreover, double-density configurations and advanced optode arrangements can refine spatial resolution, enabling researchers to better capture subtle activity patterns in targeted cortical areas.

Pre-processing of the fNIRS signals

High-quality data preprocessing is integral to extracting meaningful neural signals from raw fNIRS measurements. Systematic quality control (SQC) identifies and discards poor-quality channels, while artifact detection and removal strategies help eliminate physiological interference and environmental noise [83, 93, 94]. Frequency-selective filtering, non-stationary noise mitigation, and state-of-the-art techniques like machine learning-based artifact correction enhance the signal-to-noise ratio. By following established preprocessing guidelines and employing standardized pipelines, researchers increase the reliability and reproducibility of their results, laying a solid foundation for subsequent statistical analyses.

Statistical analysis of fNIRS signals

Appropriate statistical modeling techniques are essential for interpreting task-evoked changes in HbO and HbR concentrations. Methods such as block averaging, Finite Impulse Response (FIR) modeling, and canonical models of the hemodynamic response can tease out temporal and amplitude characteristics of underlying brain activity [95–98] . The careful selection of basis functions, model complexity, and regression strategies determines the balance between sensitivity and specificity. Incorporating dynamic approaches, like time warping or mixed-effects modeling, accommodates inter-individual variability and temporal misalignments. These analytic refinements improve the detection of subtle activation patterns, enabling robust inferences about cognitive, sensorimotor, or affective processes.

2.2.6 Application domains of fNIRS Technology

fNIRS technology has found broad utility across numerous research and applied domains. Its portability and tolerance to motion artifacts encourage investigations in real-world contexts, from evaluating collaborative problem-solving in interactive group tasks [99, 100] to assessing cognitive load and operator states in aviation, consumer, and educational settings [101]. In clinical research, fNIRS supports the examination of neural development in infants and children, as well as the assessment of neurological or psychiatric conditions under more ecologically valid conditions. This flexibility not only fosters a richer understanding of brain-behavior relationships but also informs translational efforts to enhance human performance, well-being, and societal engagement.

Functional Near-Infrared Spectroscopy (fNIRS) has been increasingly employed across various domains due to its unique advantages of portability and flexibility compared to other neuroimaging modalities. These attributes make fNIRS an invaluable tool in environments requiring collaborative efforts and complex task performance, as well as in the detection of mental states and studies involving special populations.

Collaborative and complex task environments

The portability and adaptability of fNIRS facilitate its use in real-world settings, enabling researchers to monitor neural activity during collaborative problem-solving and complex tasks. Collaborative Problem Solving (CPS), defined as the coordinated efforts of two or more individuals to construct and maintain shared solutions to problems [99], is recognized as a critical skill in the 21st century, especially given the prevalence of team-based work in modern society. Traditional analyses of collaborative work have utilized data sources such as speech [102], gaze [103], and body movements [104]. fNIRS adds a neurophysiological dimension to these analyses by allowing the investigation of brain activation patterns during cooperative interactions.

Recent studies have applied fNIRS to examine neuronal activation and cognitive workload in novice sensor operators engaged in complex tasks, such as those performed by unmanned aerial system operators [101]. Additionally, fNIRS has been utilized to measure cerebral cortex activation in multiple subjects simultaneously during group interpersonal interactions [100], enabling the study of interpersonal synchronization and the differential brain and behavioral responses between social and non-social conditions [86]. Furthermore, fNIRS has been employed to decode attended spatial locations and to analyze brain regions involved in complex scene analysis [105]. In aviation research, fNIRS has assessed operators' mental states during demanding tasks like helicopter piloting by analyzing prefrontal cortex activity [106].

These applications underscore the potential of fNIRS in advancing our understanding of group dynamics, spatial attention, and mental workload in collaborative and complex task environments.

Detection of mental states

fNIRS plays a significant role in detecting and classifying mental states, which is essential in both neuroscience research and clinical settings. While existing algorithms often treat the collected brain signals as a whole, the specific contributions of individual brain sub-regions require further investigation [107]. By analyzing changes in oxygenated hemoglobin levels during cognitive tasks, such as the operation span (OSPAN) task, fNIRS can predict cognitive performance with notable accuracy [108]. Moreover, fNIRS enables the isolation of task-evoked cortical responses from non-cerebral hemodynamic oscillations. Implementing rhythmic mental tasks allows for the separation of true neural responses from non-cerebral origins, enhancing the interpretation of fNIRS data and elucidating the dynamics of the neuro-visceral link [109]. Incorporating physiological features related to heart and breathing rates in fNIRS studies has been shown to improve the accuracy of mental workload classification [110].

Special populations and use cases

The versatility of fNIRS extends to its applications in special populations and unique use cases. fNIRS is particularly valuable for studying brain function in infants and young children, especially those with neurological, behavioral, or cognitive impairments [111]. In pediatric clinical research, fNIRS has been utilized to explore conditions such as epilepsy, communicative and language disorders, and attention-deficit/hyperactivity disorder (ADHD) [112]. Beyond clinical settings, fNIRS has demonstrated promise in consumer neuroscience, particularly in investigating consumer behavior in food marketing [113]. Its portability overcomes the mobility limitations of traditional neuroimaging tools, enabling studies involving diverse population groups, including children and individuals with obesity [114]. Additionally, fNIRS has been employed in psychiatric evaluations, aiding in the prediction of psychiatric symptoms and treatment responses in children and adolescents with ADHD and autism spectrum disorder. Overall, fNIRS serves as a valuable tool for understanding brain function and behavior across various special populations and contexts.

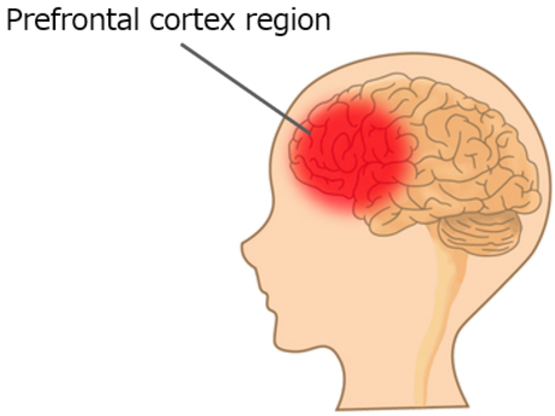

Figure 2.1: Location of Prefrontal Cortex region

2.3 The Role of the Prefrontal Cortex and Parotid Gland Region

The prefrontal cortex (PFC) is central to higher cognitive functions and is deeply involved in decision-making, emotional regulation, reward evaluation, and self-control [115](Figure 2.1 shows the location of prefrontal cortex region.). Specifically, the PFC plays a crucial role in responses to food stimuli and the regulation of eating behaviors. It is well-established that the PFC exhibits functional asymmetry between the left and right hemispheres. Davidson demonstrated that the left PFC is associated with positive emotions and approach behaviors, while the right PFC is linked to negative emotions and avoidance behaviors [60]. This asymmetry suggests differential roles of the left and right PFC in emotional value evaluation.

Research indicates that visual food stimuli elicit activity in the PFC, influencing appetite and eating behaviors. Killgore and Yurgelun-Todd reported increased PFC activity when participants viewed images of high-calorie foods, which was associated with heightened desire and reward evaluation of the food [24]. Hare et al. found that PFC activity is related to self-control during the selection of healthy foods, highlighting the PFC's significant role in regulating eating behavior [116]. Similarly, Goldstone et al. observed that PFC activation in response to food stimuli correlates with appetite and the amount of food intake [117].

The parotid gland is one of the primary salivary glands and plays a central role in saliva production (Figure 2.2 shows the location of parotid gland region.). Salivary secretion is a key component of the "cephalic

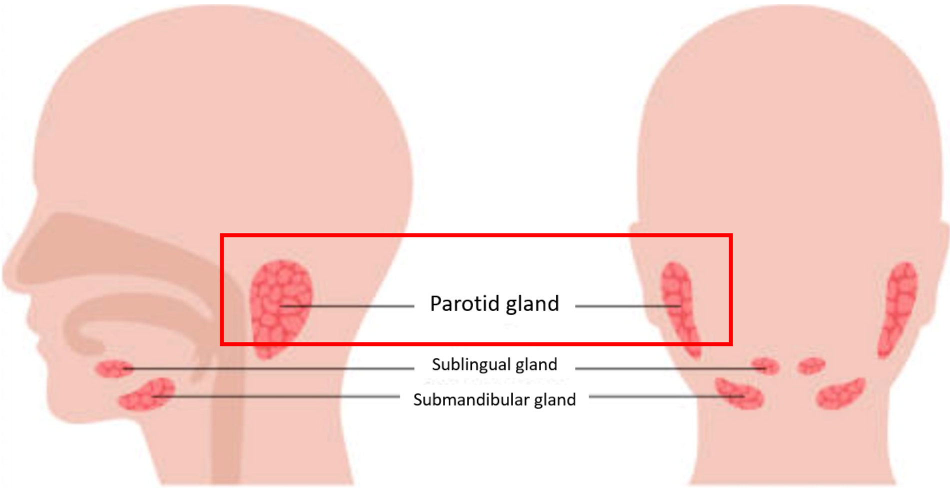

Figure 2.2: Location of parotid gland region

phase response," a preparatory mechanism for food intake that is critical in triggering physiological adaptations to food cues. Pavlov's pioneering work provided early evidence that visual food stimuli can elicit salivary secretion through conditioned reflexes, illustrating how autonomic pathways mediate physiological responses to food-related cues [23]. Subsequent research by Nederkoorn et al. has shown that both images and odors of food can enhance salivary flow, thereby heightening appetite and influencing eating behaviors [21]. In a related study, Teo et al. demonstrated that high-calorie food images robustly induce salivary secretion, which is in turn positively correlated with a stronger desire for these foods [22].

Beyond the sensory aspects of salivation, it is well established that local blood flow around the parotid gland increases in response to taste stimulation, ensuring adequate delivery of oxygen and nutrients required for saliva production [118]. Moreover, evidence suggests that functional near-infrared spectroscopy (fNIRS) signals detected over the parotid region do not originate from cortical activity; instead, they reflect physiological changes associated with salivary secretion. Hence, a portion of the hemoglobin concentration fluctuations recorded around the parotid region appears closely tied to glandular activity. Monitoring these hemoglobin changes via fNIRS thus offers an indirect, yet practical means of evaluating salivary secretion and its physiological underpinnings in real time.

Salivary secretion within the parotid gland is predominantly governed by the autonomic nervous system, particularly through branches of the submandibular ganglion and the glossopharyngeal nerve (cranial nerve IX). Taste information travels from peripheral nerve endings to the brainstem (e.g., the medulla), and then projects to higher-order gustatory processing centers, such as the anterior insular cortex and the frontal operculum [119]. During this neural relay, the salivary nucleus, located in the lower medulla, issues commands to modulate parotid gland activity, implying a robust neural network linking taste perception to the physiological processes governing salivation.

The autonomic reflex underlying saliva secretion typically manifests as increased blood flow surrounding the parotid gland, while concurrent blood flow changes in cortical regions are thought to reflect higher-order processes like taste perception and emotional assessment. From a methodological standpoint, distinguishing between blood flow signals attributable to parotid gland activity and those arising from cortical responses is crucial for accurately interpreting the overall physiological response to food stimuli [119]. Such differentiation is especially important in research employing fNIRS to investigate taste perception, salivary secretion, and their combined roles in shaping feeding behavior.

Interactions between the PFC and the parotid gland region suggest a linkage between cognitive processes and physiological responses. Previous studies propose that PFC activity may influence not only subjective evaluations and decision-making in response to food stimuli but also physiological responses such as salivary secretion. Okamoto et al. reported a correlation between PFC activity and the amount of salivation in response to visual food cues, particularly noting that increased activity in the left PFC was associated with enhanced salivary secretion [120].

Despite these insights, several unresolved issues remain. The mechanisms by which PFC activity affects salivary secretion are not fully elucidated. Detailed investigation into the neural pathways connecting cognitive evaluations and physiological responses mediated by the autonomic nervous system is necessary. Responses of the PFC and parotid gland to food stimuli may vary based on personal preferences, cultural backgrounds, and eating habits. Studies considering these individual differences are still limited, which restricts the generalizability of findings. While many studies utilize static food images, there is a lack of research on how the PFC and parotid gland respond to dynamic food videos. Employing dynamic stimuli that simulate real-life eating environments is essential for measuring more realistic reactions. Although associations between left-right PFC activity and salivary secretion have been observed, their functional significance and underlying mechanisms remain unclear. Further research is needed to determine how hemispheric asymmetry influences appetite and eating behaviors.

Chapter 3

Experimental Methodology

3.1 Participants

Seventeen healthy students (5 females, 12 males, aged 25-30) from Japan Advanced Institute of Science and Technology were recruited for this study. The participants, all graduate students, were randomly selected based on their willingness to participate. Prior to the experiment, participants underwent a screening session to confirm eligibility. A questionnaire was conducted to gather data on age, gender, and medication status. All participants were nonsmokers and exhibited no signs of systemic or oral diseases, such as periodontal disease. In addition, the participants' body mass index (BMI) ranged between 18.5–25 kg/m^2, as individuals with a BMI outside this range were excluded due to the potential impact on saliva secretion [121].

Participants with any dental pathologies or issues related to chewing and swallowing were also excluded, as these factors could affect saliva secretion [13] [122]. Subjects were informed that they would be shown photos and videos of ice cream and asked to complete rating tasks as part of the experiment. The study was conducted from March 15 to March 23, 2022, with full informed consent obtained from each participant. On the experiment day, participants were instructed to refrain from eating for one hour before the session, although they were allowed to drink water (excluding sugary beverages). Each participant received 3,000 yen as compensation for their time and cooperation.

3.2 Data Collection

3.2.1 Experimental Device

In this experiment, two advanced measurement devices were employed to assess cerebral blood flow. One is the HOT-2000 device, which measures cerebral blood flow in the prefrontal cortex, associated with cognitive function, and the WOT-S20 device, which designed to track blood flow changes

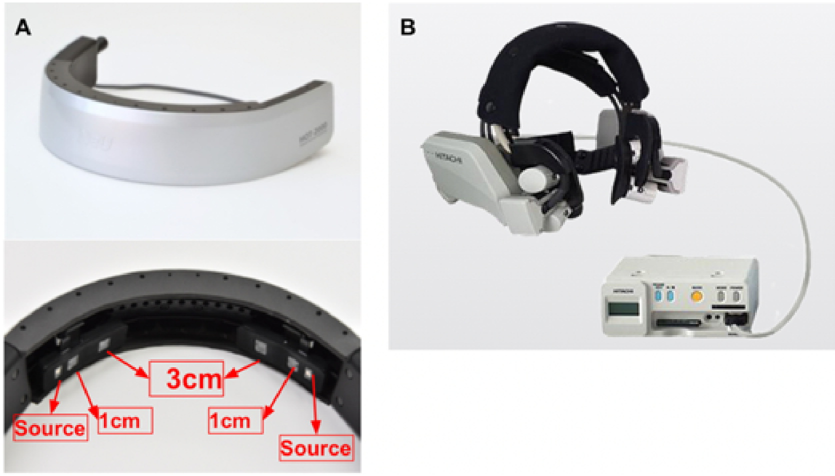

Figure 3.1: Experimental Devices. A: HOT-2000 device; B: WOT-S20 device.

in the parotid gland, a region linked to saliva secretion.

We measured cerebral blood flow using the HOT-2000. It is a portable brain activity measurement device that can be used in everyday scenarios to simultaneously measure cerebral blood flow change, pulse and head acceleration in real-time [123]. The device used in this study has two Source-Detector (SD) optode pairs. Each optode pair has two optical detectors located at a distance of 1 cm and 3 cm from the light source. The device emits a wavelength of infrared light (about 800 nm) that is easily absorbed by hemoglobin in the blood and the detected light was sampled at a frequency of 10 Hz. The measurement principle is that the infrared light irradiated from the scalp diffuses, and if the area of the brain that is in the path of the light is activated, the amount of light that returns to the detector decreases due to increased blood flow and increased light absorption. The intensity change of the detected light was converted to total-hemoglobin (HbT) on the optical path of concentration using the modified Beer-Lambert law [124]. The 1cm-SD optode pair is the short separation channel, which provides auxiliary signals from shallow tissues such as the scalp and skull, and we use it to measure what is happening in the scalp and separate brain signals from non-neuronal physiological signals. In contrast, the 3cm-SD optode pair is the long separation channel that reaches the cerebral cortex and reflects blood flow changes associated with neural activity, usually measuring the brain.

We used WOT-S20, a near-infrared optical measuring device for the lateral face (developed by NeU Corporation), to measure cerebral blood flow changes in response to saliva secretion. The WOT-S20 device consists of three components: a headset equipped with a near-infrared light receiving/emitting sensor (one channel each for left and right), a portable control box for wireless data transmission and backup functions, and a measurement controller for real-time display and storage of measurement settings and results [125]. Among them, the source emits infrared light at wavelengths of 705[nm] and 830[nm] to detect hemoglobin changes (Oxy-hemoglobin (HbO), Deoxy-hemoglobin (HbR), Total-hemoglobin (HbT)) in the blood and to capture data at a frequency of 5 Hz. The basic principle of the measurement is that an increase in saliva secretion in the parotid region promotes an increase in blood volume, which decreases the amount of light transmission.

3.2.2 Experimental Materials

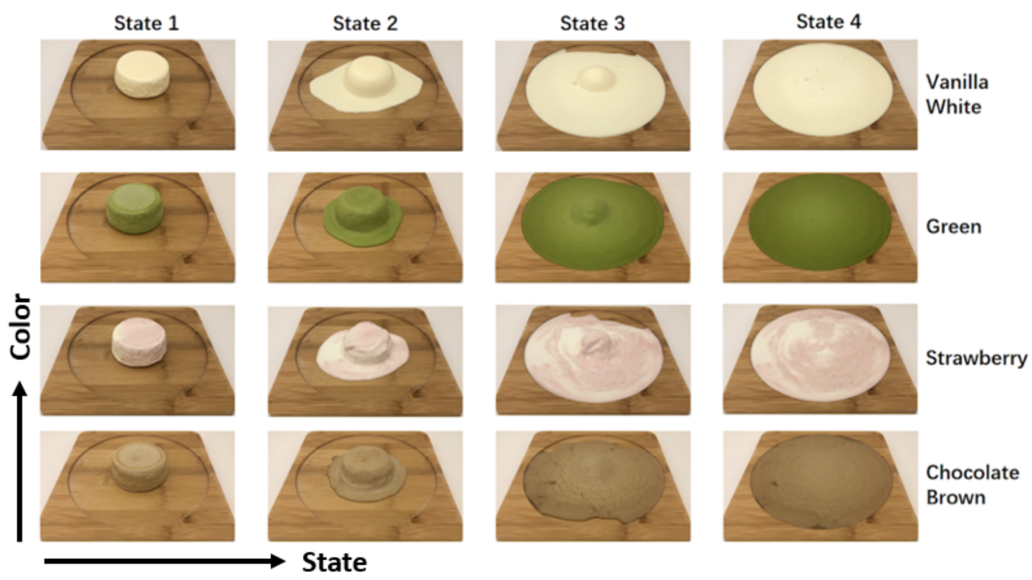

Figure 3.2: Experimental Material

For the experimental material, we chose ice cream, a food commonly found in Japanese culture. Four of the most popular ice cream flavors were selected from various commercially available ice cream products and used as experimental materials. The four ice cream flavors selected were matcha, chocolate, strawberry, and vanilla. The ice cream melting process was documented on video by placing each ice cream on a wooden plate and filming the process from hard to wholly melted. Then, we used programming to calculate the area of each state of ice cream during the process from hard to melt. Finally, the ice cream was divided into four states based on the calculated area.

In the first stage, only the middle of the ice cream has the characteristic of beginning to melt. In the second stage, the ice cream melts rapidly. In the third stage, the ice cream is still melting, but the melting rate of the ice cream is easing, and finally, in the fourth stage, the general area has not changed much. The fourth stage was a state in which only the middle of the ice cream was melting, although the general area did not change much.

Then, one representative photo was extracted from each video, and the 16 photos and 16 videos constituted the experimental material database for this experiment.

3.2.3 Experimental Environment

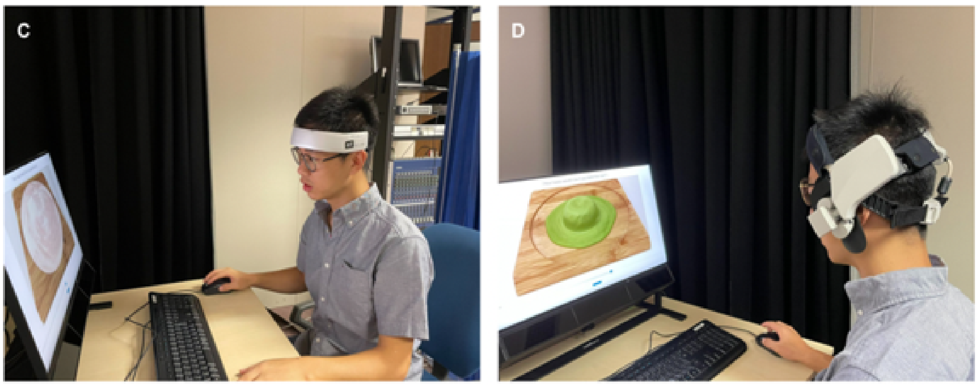

Figure 3.3: Experimental Environment. C: Experimenting with the HOT-2000 device, D: Experimenting with the WOT-S20 device.

The experimental environment is shown in Figure 3.3. Figure c on the left shows the subject using the HOT-2000 device and doing the experimental task. Figure d on the right shows the subject wearing the WOT-S20 device and participating in the experiment.

3.2.4 The Flow of the Experiment

In this section, we detail the experimental procedures designed to assess explicit and implicit food preferences, drawing on the methodology established by the Leeds Food Preference Questionnaire [126]. The experiment comprised six tasks (Tasks 1 through 6), conducted sequentially to capture both the subjective ratings of ice cream stimuli (Tasks 1–4) and participants' implicit decision-making dynamics (Tasks 5–6). Figure 3.4 presents an overview of the experimental flow, from participant preparation and initial screening to the final forced-choice selections.

The Leeds Food Preference Questionnaire was developed to examine the "liking" and "wanting" components of subjective evaluations of food, which has been reported as a valid method for measuring explicit and implicit aspects of food. Moreover, the Leeds Food Preference Questionnaire is a computer-based task that collects ratings, choices, and reaction times to visual food stimuli from different food categories [127]. Building on this foundation, our study adapted the questionnaire to focus on ice cream images and videos in four different states and colors, thereby allowing us to study how both static and dynamic presentations, and colors influence food preference decisions.

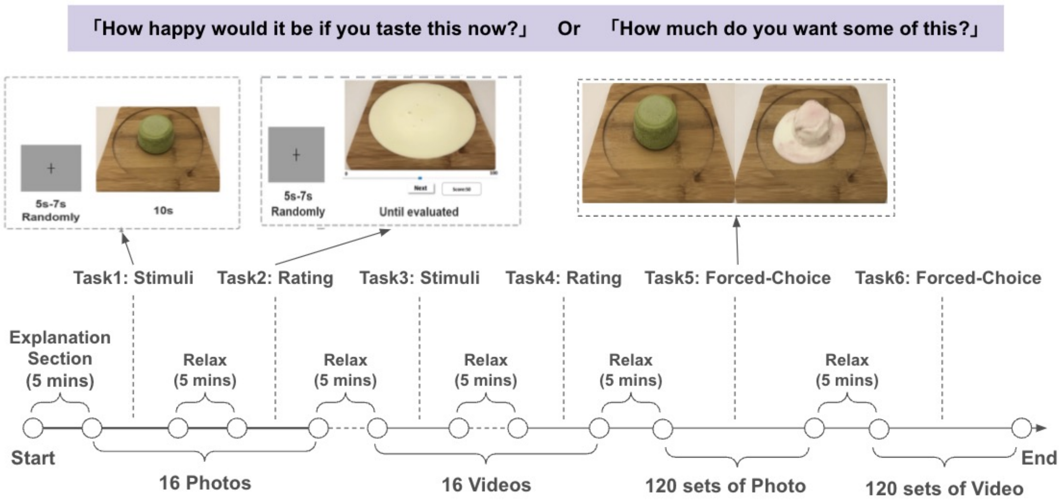

Figure 3.4: Overview of the Experimental Flow

3.2.4.1 Evaluating Explicit Food Preferences (Tasks 1–4)

Participant Screening and Preparation

Participants were tested in a controlled laboratory environment, having arrived one hour after their last meal (only water intake permitted) to ensure a standardized hunger/satiety state. After explaining the criteria for participation, the purpose, and content of the study, and confirming the subjects' eligibility, each participant completed a preliminary questionnaire collecting demographic and behavioral information (e.g., age, BMI, frequency of ice cream consumption, and subjective ice cream preferences).

Following this preparatory phase, participants began the core evaluation tasks, structured into two main blocks (see Figure 3.4): one for photo-based stimuli (Tasks 1 and 2) and one for video-based stimuli (Tasks 3 and 4). Each block incorporated a passive viewing phase followed by an explicit rating phase, capturing both “liking” and “wanting” responses. Participants were first guided through Tasks 1–4, which were designed to collect both subjective and physiological responses—most notably cerebral blood flow in the prefrontal and parotid regions—to static and dynamic ice cream stimuli.

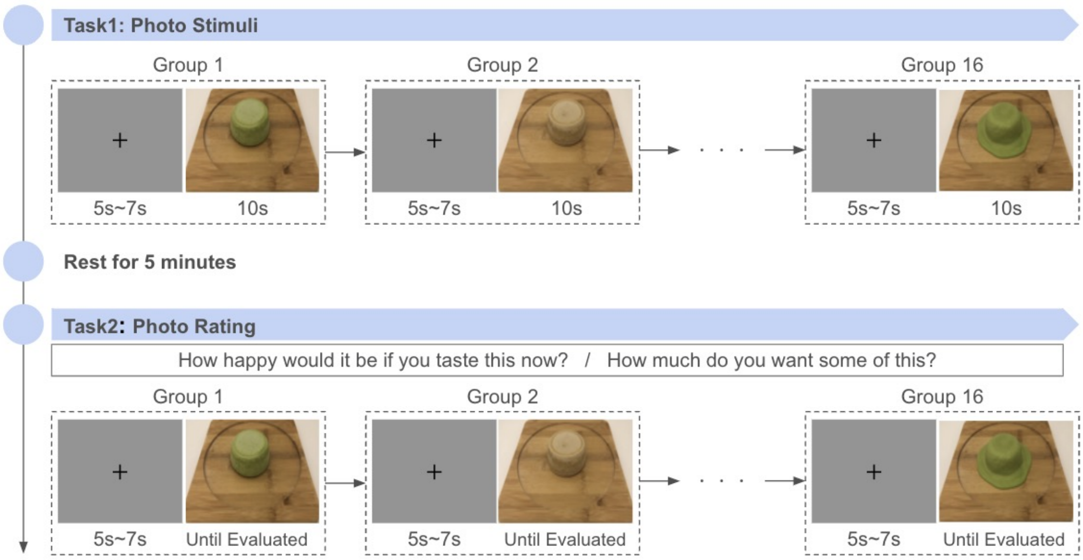

Figure 3.5: Tasks 1 and 2: Photo Stimuli and Rating

Task 1 (Photo Stimuli Presentation)

Objective: Expose participants to 16 static images of ice cream, each presented twice in randomized order, to measure the responses of cerebral blood flow during passive viewing.

Procedure (Figure 3.5):

1. A fixation cross was shown for 5–7 seconds (randomly varied) to centralize gaze and reduce anticipatory effects.
2. One ice cream image was displayed for 10 seconds, during which participants simply observed the stimulus.
3. After each image was shown, a brief rest interval occurred or the fixation cross reappeared, and the next trial began.

Presenting each image in a passive context allowed participants to engage with the visual aspects of the ice cream without immediately providing conscious evaluations. This phase also optimized conditions for measuring potential physiological responses (e.g., salivary response) associated with viewing appetite stimuli.

Task 2 (Photo Rating)

Objective: Gather explicit ratings of "liking" and "wanting" for the same 16 images viewed in Task 1.

Procedure (Figure 3.5):

1. After a fixation cross (5–7 seconds), the same ice cream image from Task 1 reappeared.
2. Participants rated the image on a 100-point visual analog scale (VAS). Two questions were asked in random order:
   - "How happy would you be if you tasted this now?" (a proxy for liking)
   - "How much do you want some of this now?" (a proxy for wanting)
3. Each rating was provided before proceeding to the next image. The randomization of "liking" vs. "wanting" questions minimized order effects.

By pairing the passive viewing phase (Task 1) with explicit ratings (Task 2), it is possible to capture participants' conscious valuations of the same stimuli. This two-part process yields a more comprehensive measure of each participant's food preferences toward static ice cream images.

Task 3 (video Stimuli Presentation)

Objective: Assess how dynamic cues influence explicit preference by presenting participants with 16 short ice cream videos (each 10 seconds in length).

Procedure (Figure 3.6):

1. Each trial began with a 5–7 second fixation cross, followed by a 10-second video showcasing ice cream in a dynamic state (e.g., melting).
2. As in Task 1, participants were instructed to passively view the videos without providing any immediate rating.
3. A 5-minute rest interval was introduced after the full set of videos to prevent fatigue and maintain attentiveness.

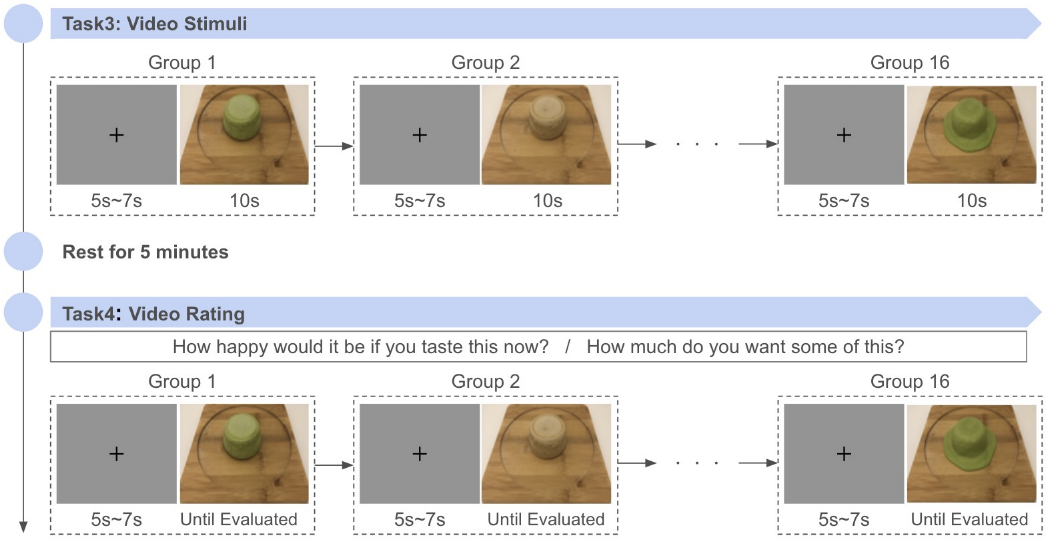

Figure 3.6: Tasks 3 and 4: Video Stimuli and Rating

Presenting videos allowed participants to observe motion, which can heighten sensory appeal and potentially influence preference formation. Comparing these dynamic stimuli ratings (later obtained in Task 4) with those from static images helps clarify whether movement augments perceived palatability or desire.

Task 4 (video Rating)

Objective: Collect explicit "liking" and "wanting" evaluations for the 16 ice cream videos from Task 3.

Procedure (Figure 3.6):

1. After a 5–7 second fixation cross, each 10-second video was replayed in a new trial, prompting participants to provide two VAS ratings in randomized order (liking vs. wanting).
2. A 5-minute rest interval followed the completion of all video ratings, mirroring the structure of the photo-based tasks.

By mirroring the structure of Tasks 1–2 with dynamic stimuli, the study obtains comparable measures of explicit preference across both static and video formats. This design facilitates a direct comparison of whether movement and visual complexity bolster an item's "liking" or "wanting" scores.

3.2.4.2 Evaluating Implicit Food Preferences (Tasks 5–6)

After completing the explicit preference assessments (Tasks 1–4), participants proceeded to the forced-choice selection tasks (Tasks 5 and 6). These tasks were designed to measure implicit aspects of food preference by examining reaction times and the speed with which participants selected preferred stimuli when presented with two options simultaneously. The forced-choice paradigm captures cognitive processes that may not be fully accessible through explicit ratings alone, offering insights into the implicit determinants of food selection. Figure 3.7 illustrates the forced-choice procedures for both photo and video stimuli.

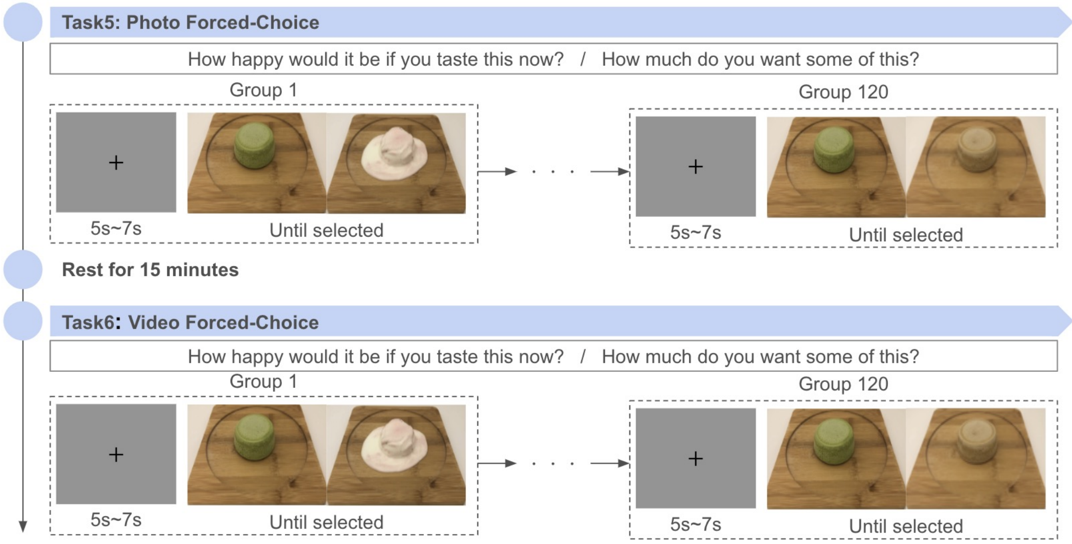

Figure 3.7: Tasks 5 and 6: Photo and Video Forced-Choice

Task 5 (Photo Forced-Choice):)

Objective: Investigate implicit preferences using paired ice cream images to measure selection patterns and reaction times under time pressure.

Procedure (Figure 3.7):

1. Each trial started with a fixation cross (5–7 seconds).
2. Two ice cream photos (from the Task 1–2 stimulus pool) were displayed side by side on the screen.
3. Participants indicated which image they preferred by clicking on it as quickly as possible (up to 10 seconds).

4. Reaction times (RTs) were recorded to the nearest millisecond, capturing the speed of participants' decisions. If no response occurred within 10 seconds, the trial ended without a recorded preference.
5. Counterbalancing ensured that each stimulus appeared equally on both left and right sides across trials, minimizing positional bias.

Forced-choice paradigms tap into automatic or habitual preference processes, potentially revealing influences that might not emerge in explicit ratings alone. Shorter RTs can reflect stronger underlying preferences or heightened motivational salience.

Task 6 (Video Forced-Choice):

Objective: Extend the implicit preference assessment to dynamic ice cream videos, mirroring Task 5's forced-choice structure.

Procedure (Figure 3.7):

1. As in Task 5, each trial began with a 5–7 second fixation cross.
2. Two short ice cream videos (from the Task 3–4 stimulus pool) appeared concurrently on the screen.
3. Participants clicked on the video they preferred, and the system recorded the reaction time (up to 10 seconds).
4. Presentation order and left/right positioning were systematically randomized to mitigate order effects.

Comparing RTs and selection outcomes for dynamic stimuli offers insights into how movement or melting cues may differentially influence implicit preference formation, revealing potentially stronger or weaker motivational pulls compared to static images.

3.2.4.3 Integration of Explicit and Implicit Measures

By coupling explicit (Tasks 1–4) and implicit (Tasks 5–6) measurements, the experimental design provided a multidimensional profile of each participant's food preferences. Explicit ratings yielded quantitative measures of subjective "liking" and "wanting," while forced-choice selections captured the implicit decisional processes underlying preference formation. Together, these measures offer a nuanced understanding of how participants consciously and unconsciously respond to appetitive food cues—shedding light on the interplay between deliberative preference formation and automatic decision-making.

This integrated methodological approach facilitates a broader comprehension of real-world food choice behavior, wherein both conscious valuations and rapid, less deliberative processes shape dietary decisions. By drawing on measures from both domains, the study enables a comprehensive examination of preference formation that encompasses attentional, cognitive, and motivational components of ice cream selection.

3.2.5 fNIRS Data Collection

In this study, we focused on the prefrontal and parotid brain regions. During the experiment, data were collected by measuring each subject's cerebral blood flow data in each task. When measuring cerebral blood flow in the prefrontal cortex, subjects' resting cerebral blood flow was measured for 5 minutes before the experiment. When measuring resting cerebral blood flow, subjects were instructed to sit on a chair, close their eyes, and rest as relaxed as possible. Five minutes of resting cerebral blood flow data were used as training data for fNIRS data processing.

Chapter 4

Data Analysis and Results

4.1 Data Analysis

4.1.1 fNIRS Data Processing (saliva)

The raw cerebral blood flow data on saliva collected are HbO, HbR, and HbT, where HbT is the sum of HbO and HbR. For the processing of fNIRS data in the parotid region, we first convert the data output from the machine to Shared Near Infrared Spectroscopy Format (SNIRF), developed by the Society for functional Near Infrared Spectroscopy [128]. Then, a general linear model (GLM) [129] was performed for processing the fNIRS data in the parotid region using the open-source HOMER3 toolbox [130] in MATLAB (Mathworks Inc.). The procedure was as follows: Firstly, we used the prune channel function to prune bad or low SNR channels from the measurement list. Next, the raw light intensity signal was converted to optical density. Bandpass filtering was applied to the fNIRS data in the 0-0.5 Hz range. The optical density was then converted to total hemoglobin (HbT) concentration with a default partial path length factor. Finally, a general linear model (GLM) was used to remove whole-body artifacts. The hemodynamic response function (HRF) was estimated using the mean of the long separation channels. A continuous Gaussian function (stdev=1.0, step=1.0) was calculated from rest to speech.

4.1.2 fNIRS Data Processing (PFC)

For the processing of fNIRS data in the prefrontal region, we converted the data to the Shared Near Infrared Spectroscopy Format (SNIRF). Then, the general linear model with temporally embedded canonical correlation analysis (GLM with tCCA) [129] was conducted using the open-source HOMER3 toolbox [130] in MATLAB (Mathworks Inc.). Firstly, the prune channel's function was used to prune bad or low SNR channels from the measurement list. Then we converted the raw optical intensity signal to an optical density. Subsequently, both fNIRS and auxiliary data were conducted the bandpass filtering within 0-0.5 Hz. Then, we converted the optical density to total-hemoglobin (HbT) concentration with default partial path-length factor. Now, to reduce nuisance signals in fNIRS and create optimal regressors, the temporally embedded Canonical Correlation Analysis function was conducted. Finally, a general linear model (GLM) was used to remove the systemic artifacts. The hemodynamic response function (HRF) was estimated using the average of the long separation channels. It was calculated with the consecutive sequence of Gaussian functions (stdev=1.0, step=1.0) from rest to the speech period.

4.1.3 Statistics Analysis

Subjective rating scores for each ice cream were collected during the subject's experiment, and the mean value of each rating score was calculated. After processing the cerebral blood flow data, the mean value and the change of cerebral blood flow signal for each channel were calculated. After confirming the normality of the data, correlations were calculated between subjects' subjective evaluation data and objective fNIRS data.

4.2 Results of Ice cream Evaluation

The evaluation outcomes for the ice cream stimuli are summarized in Table 4.1, which shows the mean "liking" and "wanting" ratings from photos and videos, organized both by ice cream color and melting state. These values reflect participants' responses to the questions "How happy would you be if you tasted this now?" (liking) and "How much do you want some of this now?" (wanting). The following sections detail the findings for each factor—melting state and color—and discuss them in the context of existing literature.

4.2.1 Influence of Color

Comparing ice cream by color, when subjects were asked how happy they would be if they tasted the ice cream then in response to a photo of ice cream, the mean rating of ice cream in each state was 23.75 for vanilla white and 23.24 for green, 24.02 for strawberry ice cream color, and 20.00 for chocolate brown. When subjects were asked how much they would like this food then in response to a picture of ice cream, the mean rating of ice cream in each state was 26.34 for vanilla white and 26.84 for green, 27.20 for strawberry ice cream color, and 20.55 for chocolate brown. On the other hand, when

Table 4.1: Ice Cream Rating results

			Liking_Photo	Wanting_Photo	Liking_Video	Wanting_Video
Color	Vanilla White		23.75	26.34	23.09	24.07
	Green		23.24	26.84	26.00	24.67
	Strawberry		24.02	27.20	22.52	27.66
	Chocolate Brown		20.00	20.55	23.02	21.11
State	State1		56.59	63.59	52.59	56.41
	State2		15.04	22.53	28.22	26.84
	State3		9.52	8.77	9.77	8.23
	State4		9.36	5.43	5.89	1.89

Note: The numbers in the table is the mean value of the evaluation.

subjects were asked how happy they would be if they ate the ice cream in response to a video of ice cream, the mean rating of ice cream in each state was 24.07 for vanilla white and 24.67 for green, 27.66 for strawberry ice cream color, and 21.11 for chocolate brown, when subjects were asked how much would you like this food now in response to a video of ice cream, the mean rating of ice cream in each state was 23.09 for vanilla white and 26.00 for green, 22.52 for strawberry ice cream color, and 23.02 for chocolate brown.

To examine whether there were statistically significant differences in the mean evaluation scores across colors, a one-way analysis of variance (ANOVA) was conducted. The results indicated that there were no significant differences in the evaluation scores among the colors ($F(3, 64) = 0.801$, $p = 0.452$). Nevertheless, when looking at the group means, color still appears to play an important role in participants' subjective evaluations. Strawberry (a pinkish hue) consistently emerged with the highest mean ratings for both "liking" and "wanting," especially in the video format, whereas Chocolate Brown achieved the lowest mean ratings across both photos and videos. Green and Vanilla White generally occupied intermediate positions, although Green outperformed Vanilla White in some measures. Thus, despite the absence of a statistically significant difference, these mean scores suggest that color exerts a noteworthy influence on how participants perceive and desire ice cream.

4.2.2 Influence of Melting State

Comparing ice cream by state, when subjects were asked how happy they would be if they tasted the ice cream at that moment in response to a photo of ice cream, the mean rating of ice cream in each state was 56.59 for State 1 and 15.04 for State 2, 9.52 for State 3, and 9.36 for State 4. When subjects were asked how much they would like to eat the ice cream in the picture, the mean rating of ice cream in each state was 63.59 for state 1 and 22.53 for state 2, 8.77 for state 3, and 5.43 for state 4, on the other hand, when subjects were asked how happy they would be if they ate the ice cream in response to a video of ice cream, the mean rating of ice cream in each state was 52.59 for state 1 and 28.22 for state 2, 9.77 for state 3, and 5.89 for state 4, when subjects were asked how much would you like this food now in response to a video of ice cream, the mean rating of ice cream in each state was 56.41 for state 1 and 26.84 for state 2, 8.23 for state 3, and 1.89 for state 4.

To examine whether there were statistically significant differences in the mean scores of subjective evaluations across conditions, a one-way analysis of variance (ANOVA) was conducted. The analysis revealed significant differences in subjective evaluation scores among the conditions ($F(3, 64) = 4.317$, $p = 0.0051$). Participants' evaluations varied markedly across the four melting states (State 1 through State 4). When viewing photos, the highest mean ratings for both liking and wanting appeared at State 1 (i.e., 56.59 and 63.59, respectively), indicating a strong preference for ice cream that appeared fresh and largely intact. In contrast, more melted forms (States 2–4) showed pronounced declines, with ratings for State 4 dropping to single digits (9.36 for liking and 5.43 for wanting). A similar pattern emerged for the video stimuli, where State 1 retained the highest ratings (52.59 for liking and 56.41 for wanting), whereas progressive melting correlated with a steady reduction in subjective appeal.

4.2.3 Comparison of Photos versus Videos

While the presentation modality (photo vs. video) did not drastically alter the overall preference hierarchy (i.e., participants tended to favor the same flavor and melting states regardless of format), videos often prompted slightly higher ratings. This modest elevation, especially noticeable for Strawberry, could stem from the dynamic cues inherent in moving images, which might make the ice cream appear more realistic and engaging. Such an effect aligns with broader evidence suggesting that sensory richness—including motion and changes in texture—can heighten emotional and motivational responses to food.

At the same time, Chocolate Brown consistently received the lowest ratings in both media types, pointing to factors such as flavor familiarity or visual appeal that may be influencing participants' judgments. Hence, while dynamic presentation can enhance the "wanting" aspect for certain colors, less-preferred flavors and colors—like Chocolate Brown—may remain comparatively lower even when motion cues are introduced.

4.3 Results of Hemodynamic response function (HRF)

There is a positive correlation between the hemoglobin signal of cerebral blood flow in the parotid region and salivary secretion, meaning that increased cerebral blood flow activity tends to increase saliva secretion.

After processing the fNIRS data, the hemodynamic responses of cerebral blood flow in the prefrontal and parotid regions were investigated during the visual stimulation and evaluation of the ice cream. The results of activation in prefrontal and parotid regions by visual stimulation of ice cream in each state are shown in Figure 4.1 to Figure 4.3. Figures show the trend of the hemodynamic response function (vertical axis) to the stimulation of photos and videos for each ice cream state from the baseline period (-3 s to 0 s: prior to stimulation and rating of ice cream images) through the five-second interval following task onset (0 s). The purple dashed line represents the group-averaged hemodynamic response function (HRF) for total hemoglobin (HbT), and the error bars indicate the standard error. In the figures, for each ice cream condition (State1 to State4), changes in the hemodynamic response in the left and right parotid gland regions are shown during the rating phase (e.g., "StateX_Rating_left") as well as during stimulus stimulation (e.g., "StateX_left").

4.3.1 HRF of Parotid Region to Photo and video Stimuli Across States (Figure 4.1)

HRF of Parotid Region to Photo Stimuli Across States (Figure 4.1)

In Figure 4.1, each panel depicts the HRF trend in either the left or right parotid region under two conditions: the stimulation phase (e.g., "State4_left") and the rating phase (e.g., "State4_Rating_left"). According to the results of the hemodynamic response function, when subjects were asked how happy they would be if they tasted the food in response to a

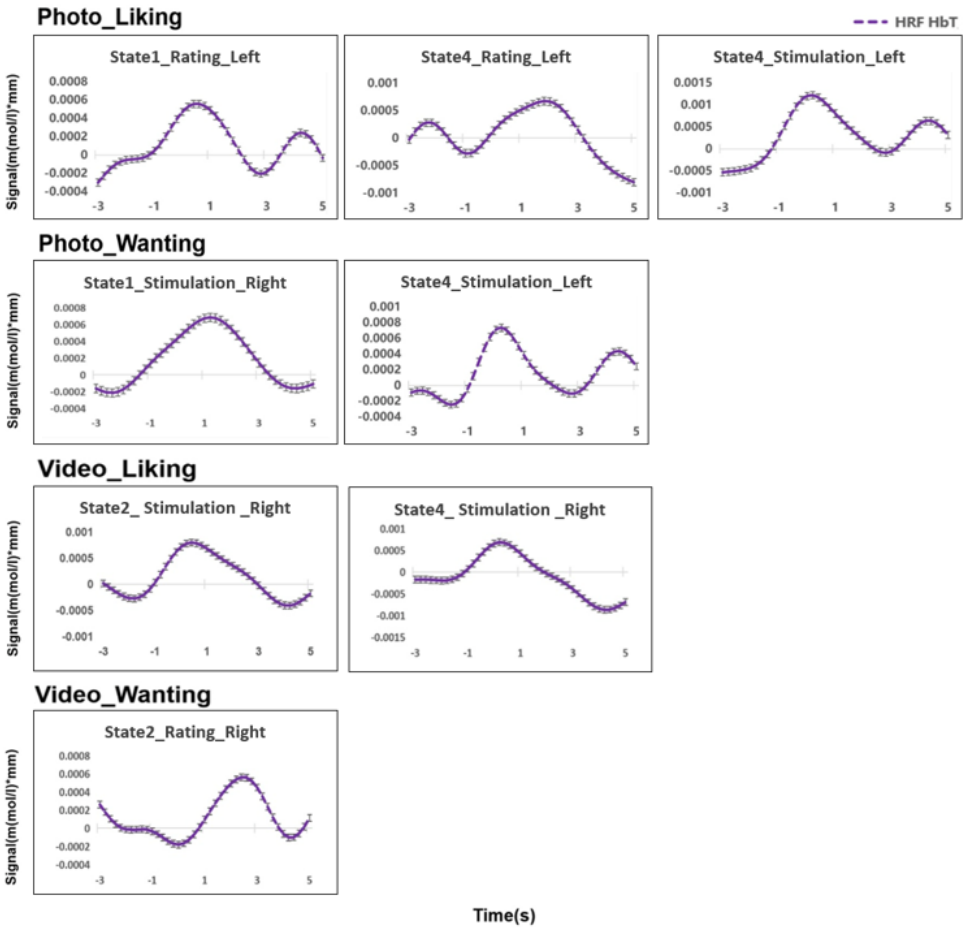

Figure 4.1: The trend of hemodynamic response function time courses of parotid region to photo and video stimuli in different states

photo of ice cream ("liking"), we observed a tendency for a stimulation-induced of increase in cerebral blood flow in the left parotid region when subjects were evaluating photos of ice cream in States 1 (least melted) and 4 (fully melted), and when they were receiving stimulation of the photo in state 4. Moreover, when subjects were asked how much they would like to eat this food in response to a photo of ice cream ("wanting"), we observed a tendency for cerebral blood flow due to stimulation to increase in the right parotid region when they were receiving stimulation of the ice cream photo in state 1. Furthermore, when they were receiving stimulation of the photo in state 4, a tendency for cerebral blood flow to increase was observed in the left parotid region during the stimulation.

When participants were receiving stimulation and evaluated ice cream photos, particularly in states 1 and 4, an increase in cerebral blood flow in the left parotid gland region was observed. This suggests that the brain's response to visual stimuli is modulated by the physical state of the food, with more pronounced neural activity being triggered in both the initial (frozen) and final (melted) states. Interestingly, the right-sided parotid gland region also showed an increase in blood flow during evaluations of state 1, indicating a lateralized response depending on the specific aspects of the task or the stimulus being evaluated. The differences in blood flow across states suggest that the early and late stages of food melting elicit stronger brain involvement. This is likely due to the contrast between the appealing nature of solid food and the less appetizing melted state. These findings highlight the importance of visual cues in determining food attractiveness, with fresh and intact states potentially stimulating stronger neural and physiological responses.

HRF of Parotid Region to video Stimuli Across States

Figure 4.1 also presents the trend of the hemodynamic response function to the stimulation of videos for each ice cream state. When subjects were asked how happy they would be if they tasted this now in response to a video of ice cream ("liking"), we observed a tendency for a stimulation-induced of increase in cerebral blood flow in the right-side parotid region during the stimulation for videos of ice cream in state 2 and state 4. Furthermore, when subjects were asked how much they would like to eat this food in response to a video of ice cream ("wanting"), a tendency for cerebral blood flow to increase was observed in the right parotid region when subjects were rating videos of ice cream in state 2.

The result shows that when subjects viewed videos of ice cream in State 2 (rapid melting) and State 4 (almost fully melted), there was a significant increase in cerebral blood flow in the right-side parotid region. This region is strongly associated with salivation, which is closely linked to appetite and desire for food. State 2 (Rapid Melting): at this stage, the ice cream still retains much of its shape but is undergoing a visually noticeable transformation, making it potentially more appetizing due to its "ready-to-eat" appearance. This stimulates the brain to prepare for consumption, increasing cerebral blood flow, especially in areas associated with physiological preparation for food intake, like salivation. State 4 (almost fully melted): Although the food is less visually appealing in this final state, the increase in cerebral blood flow in the right parotid region suggests that some subjects may still find the food desirable, likely due to contextual cues from the video (e.g., anticipation of taste even in the melted state).

Importantly, the right hemisphere has been linked to global shape recognition and emotional processing, making it well-suited to dynamic, time-based stimuli such as videos. This lateralization may explain why videos, especially those depicting transitional states of the ice cream (e.g., from a recognizable shape to melting), appear to more strongly engage the right parotid region associated with salivation and appetite [131].

Hemispheric dominance plays a crucial role in the lateralization of cognitive functions, with the left hemisphere primarily responsible for visuomotor control and language processing, and the right hemisphere governing spatial and emotional functions. This functional division enhances the efficiency of cognitive processing. Moreover, in the context of visual stimulus processing, the right hemisphere excels in recognizing global shapes, while the left hemisphere is specialized in analyzing local details.

Our findings indicate that increased cerebral blood flow in the parotid region, particularly on the right side, may reflect the brain's preparation for food consumption. This interpretation is supported by the observed increase in blood flow when participants rated their desire to consume the ice cream. The rise in cerebral blood flow in the right parotid region, particularly when participants viewed videos of ice cream in different states, may be associated with physiological processes that prepare the body for intake. Visual stimuli, such as the melting process of ice cream, are known to stimulate salivation and appetite as the brain anticipates consumption [131].

Furthermore, videos, which provide dynamic, time-based information, tend to engage more complex and sustained attentional processes compared to static images. The role of the right hemisphere in processing dynamic visual stimuli, such as videos, corresponds with the observed increase in cerebral blood flow. This hemisphere is actively involved in managing spatial and emotional processing, both essential when evaluating appetitive stimuli like food [131]. Consequently, the right hemisphere is often more engaged when individuals process dynamic stimuli, such as changing visual representations in a video. This aligns with appetite regulation, as observing the melting process of ice cream in a video may evoke a sense of urgency or readiness to consume, triggering increased salivary response and activation in the right parotid region.

Research on oral processing behavior emphasizes how sensory perceptions of ice cream can influence both consumption and appetite, indicating that the dynamic nature of ice cream, particularly in its melting state, can enhance its appeal and trigger physiological responses, such as increased salivation [131]. Additionally, sensory analyses of ice cream with varying ingredients reveal that visual and textural modifications can significantly impact consumer perception and desire to consume, which may correspond with the observed cerebral responses when viewing ice cream in different states [132].

The right hemisphere's dominance in processing global shapes and dynamic stimuli supports the hypothesis that videos of ice cream, especially in states that suggest readiness for consumption, can stimulate cerebral blood flow in regions associated with salivation and appetite [131]. Studies on the sensory properties of ice cream and its implications in dietary contexts suggest that visual and sensory cues play a significant role in influencing appetite and consumption behaviors. However, further research focused on hemodynamic responses to visual stimuli of food in different states would offer a more comprehensive understanding of these processes.

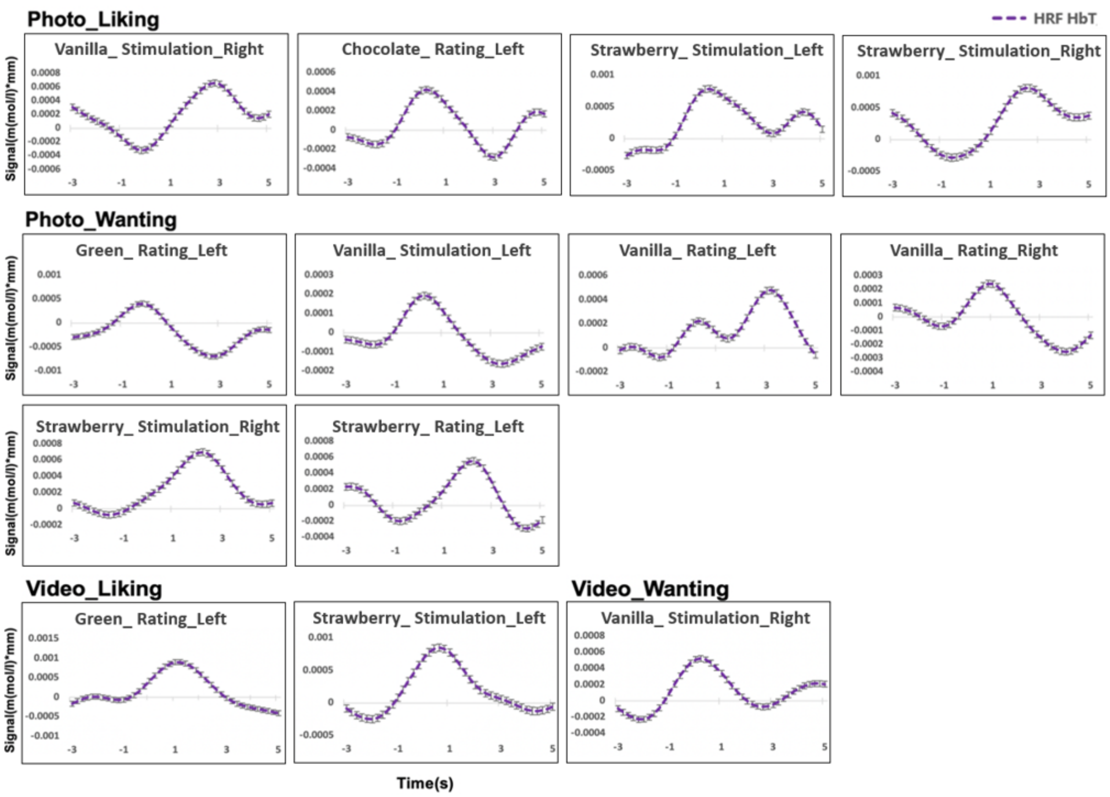

Figure 4.2: The trend of hemodynamic response function time courses of parotid region to photo and video stimuli in different colors.

4.3.2 HRF of Parotid Region to photo and video Stimuli Across Colors (Figure 4.2)

HRF of Parotid Region to photo Stimuli Across Colors (Figure 4.2)

Figure 4.2 depicts the group-averaged hemodynamic response function (HRF) in the parotid region under two conditions: the stimulation phase (e.g., "Vanilla_right") and the rating phase (e.g., "Chocolate_Rating_left") in four different colors (Vanilla White, Strawberry Pink, Chocolate Brown, and Green). The vertical axis represents the total hemoglobin signal (HbT) changes, while the horizontal axis spans from -3 seconds (baseline) to +5 seconds (post-stimulus onset). Error bars indicate the standard error of the mean.

Overall, color emerged as an influential factor in shaping the magnitude and laterality of parotid responses:

1. Vanilla White elicited an increase in cerebral blood flow, particularly in the right parotid region during "How happy would you be if you tasted this food now?" (liking). This pattern suggests that a light, neutral color may strongly engage reward-related circuits, potentially due to associations with freshness and sweetness.
2. Strawberry Pink produced heightened blood flow in both left and right parotid regions, suggesting a more robust, bilateral response. This bilateral effect is consistent with the notion that bright or warm hues can trigger stronger emotional arousal, leading to heightened salivary and motivational responses.
3. Chocolate Brown predominantly activated the right parotid region when participants rated their liking of the ice cream. This lateralization might reflect the right hemisphere's role in emotional and reward processing, though the chocolate hue appeared less likely to engage left parotid responses compared to strawberry.
4. Green was linked to an increase in left parotid region activity, especially during "How much would you like some of this now?" (wanting). This left-sided activation could indicate that the process of detailed evaluation or preference formation is more pronounced for certain less traditional dessert colors (e.g., green).

These observations underscore how visual appearance (in this case, color) can significantly influence cerebral blood flow dynamics in the parotid region, highlighting the role of visual cues in physiological responses. Moreover, the result reveals that the right parotid region predominantly responds to appetitive stimuli, while the left parotid region is associated with desire evaluation. These findings suggest that color can trigger varied neural responses related to food preference, providing critical insights into how visual cues influence reward processing and appetite. Our finding provides important insights into how visual stimuli trigger physiological responses and engage the brain's reward system. Specifically:

Color and Cerebral Blood Flow: Changes in cerebral blood flow in the left and right parotid regions varied with ice cream color, indicating that visual stimuli can provoke distinct physiological responses depending on the color. For example, "Vanilla White" led to increased blood flow in the right parotid region, suggesting a strong reward response. "Strawberry Pink" showed increased blood flow in both parotid regions, indicating heightened emotional and desire-driven responses. Similarly, "Chocolate Brown" elicited increased blood flow in the right parotid region, while "Green" stimulated increased blood flow in the left parotid region, potentially related to preference or desire evaluation.

Significance of Parotid Region Blood Flow: Lateral differences in blood flow changes in the parotid regions provide insights into how the brain processes reward and desire. For example, the right parotid region was more active in response to "Vanilla White," "Strawberry Pink," and "Chocolate Brown" stimuli. In contrast, the left parotid region was more engaged when processing preferences related to "Vanilla White," "Green," and "Strawberry Pink."

Physiological Responses Linked to Preferences and Desires: Evaluation of preferences (Liking) and desires (Wanting) showed that visual elements and their associated physiological responses are closely intertwined. Increases in cerebral blood flow in response to visually appealing foods validate the activation of the reward system and its influence on appetite and desire.

Relationship Between Visual Stimuli and Physiological Responses: The color of visually presented ice cream stimulates the brain's reward system, increasing salivation and influencing appetite and preferences. This research clarifies how food colors stimulate desire and the strength of physiological responses based on visual presentation.

Our findings align with prior literature documenting that visual food cues can elicit reward system activation and salivary responses [2, 24, 133]. Colors perceived as fresh or vivid (e.g., pink) typically enhance appetite and positive affect, thereby elevating parotid blood flow [63]. The current data reinforce the idea that color is a powerful sensory cue that can shape how appetitive or rewarding a food appears, mediating both "liking" (happiness) and "wanting" (desire).

HRF of Parotid Region to video Stimuli Across Colors (Figure 4.4)

Figure 4.4 illustrates the group-averaged HRF trends of Parotid Region to the stimulation and evaluation of videos for each ice cream color under two conditions: the stimulation phase (e.g., "Strawberry_right") and the rating phase (e.g., "Green_Rating_left") in four different colors. Compared to static photos, videos introduce dynamic cues (e.g., melting, motion) that may alter the strength and timing of neural responses:

When subjects were asked how happy they would be if they tasted the food in response to a video of ice cream, we observed a tendency for a stimulation-induced of increase in cerebral blood flow in the left parotid region when subjects were rating videos of ice cream in green color and the right parotid region when they were receiving stimulation of the video of ice cream in strawberry color. Furthermore, when subjects were asked how much they would like to eat this food in response to a video of ice cream, a tendency for cerebral blood flow to increase was observed in the right parotid region when receiving stimulation of the video of ice cream in green color.

Namely, green Videos tended to elevate cerebral blood flow in the left parotid region during "liking" and in the right parotid region during "wanting". This double-sided activation suggests that video format might amplify the salience of an unconventional dessert color, engaging distinct neural circuits for hedonic evaluation versus motivational drive. Strawberry Pink Videos primarily increased parotid region blood flow in the right hemisphere during "liking-stimulation," mirroring the broad pattern observed with photo stimuli but emphasizing dynamic visual features. The strong right-lateralized response aligns with evidence that emotional and global processing often localizes in the right hemisphere [61, 134].

The observation that changes in cerebral blood flow related to liking (how happy participants would feel after eating) and desire (how much they want to eat) occurred in different regions suggests that liking and desire are processed through distinct neural pathways in the brain. In the case of green ice cream videos, the left parotid region was activated in response to liking, while the right parotid region responded to desire, indicating that these evaluations may involve separate neural circuits. Moreover, the fact that responses to green and strawberry ice cream were observed in different regions highlights the importance of color as a factor in visual food stimuli. Certain colors may activate distinct regions of the brain, triggering unique emotional and physiological responses.

The dissociation between "liking" (happiness) and "wanting" (desire) across left and right parotid regions aligns with theoretical frameworks positing that these processes involve partially distinct neural pathways [63, 135]. Dopaminergic systems are frequently implicated in "wanting," whereas opioid systems may modulate the pleasure inherent in "liking." Visual color cues, heightened by motion in video clips, could differentially engage these pathways, generating lateralized parotid responses [24]. Conversely, there is literature that does not fully align with our findings, noting inconsistencies in how color impacts appetite. Delwiche argued that while interactions between taste and smell significantly affect flavor perception, the influence of color is highly individual [1]. These discrepancies may stem from cultural backgrounds, personal experiences, or preconceived notions about food.

4.3.3 Results of Hemodynamic response function (HRF) in the prefrontal region

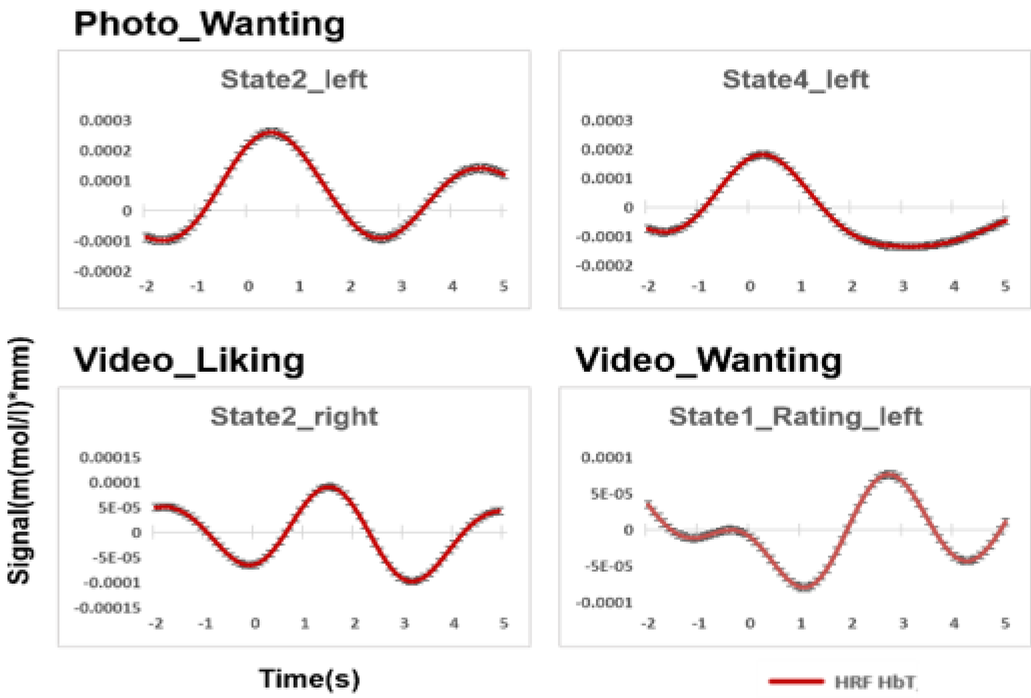

Figure 4.3: The trend of hemodynamic response function time courses of prefrontal region to photo and video stimuli in different states.

Figure 4.3 displays the time course of the Hemodynamic response function (HRF) in the prefrontal cortex when participants viewed and rated ice cream stimuli in various melting states. Two experimental phases are shown for each state: a stimulation phase (e.g., "State2_left") and a rating phase (e.g., "State1_Rating_left"). The horizontal axis marks time from -2 to 5 seconds relative to stimulus or rating onset (time 0), and the vertical axis indicates the group-averaged change in cerebral blood flow. The red solid line represents the mean HRF trajectory for total hemoglobin (HbT), and the error bars denote the standard error of the mean across participants. By comparing the mean cerebral blood flow in the 2-second baseline period (-2s to 0s) with that observed up to 5 seconds post-onset, it is possible to estimate how prefrontal activity responds to different melting states under both static (photo) and dynamic (video) conditions.

Photo Stimuli and Prefrontal Activation

According to the results of the HRF results for photo stimuli, when subjects were asked how much they would like to eat this food in response to a photo of ice cream, we observed a tendency for cerebral blood flow due to stimulation to increase in the left prefrontal region when they were receiving stimulation of the ice cream photo in state 2 (rapidly melting) and state 4 (almost fully melted). In the case of State 2 and State 4 photo stimuli, an increase in cerebral blood flow was observed in the left prefrontal cortex when participants receiving stimulation. This suggests that the visual presentation of food, particularly in transitional states such as rapidly melting ice cream (State 2) or moderately melted (State 4), plays a significant role in eliciting appetite-related neural responses. This result underscores the importance of transitional states: as the ice cream softens but remains visually consumable, it appears to heighten motivational responses associated with appetite. These observations align with prior research linking the left prefrontal cortex to reward anticipation and goal-directed behavior, particularly for "wanting" [56, 136–138].

video Stimuli and Prefrontal Activation

In video stimuli, when subjects were asked how happy they would be if they tasted the food in response to a video of ice cream, a tendency for cerebral blood flow due to stimulation to increase in the right prefrontal region when they were receiving stimulation of the ice cream video in state 2. In this case, State 2 again proved notable, but this time for increased activity in the right prefrontal cortex when participants receiving stimulation from the ice cream ("liking"). Unlike static images, dynamic cues—such as melting drips—may intensify the sensory appeal and emotional engagement, thus recruiting the right hemisphere, which has been linked to broader emotional processing [60, 61]. This enhanced response suggests that videos depicting rapidly melting ice cream can elevate the hedonic (pleasure-related) dimension of food evaluation. Additionally, when subjects were asked how much they would like to eat this food in response to a video of ice cream, a tendency for cerebral blood flow to increase was observed in the left prefrontal region when subjects were rating videos of ice cream in state 1. Namely, State 1 (largely intact ice cream) videos prompted heightened left prefrontal cortex activation during the wanting evaluation, reflecting the role of fresh and visually appealing stimuli in heightening desire to consume. The intact appearance could be perceived as fresher or more appealing, thereby amplifying motivational drive. Overall, these patterns reinforce a hemispheric specialization, whereby left-prefrontal regions appear more attuned to "wanting" and right-prefrontal regions more responsive to "liking" in dynamic food contexts [66, 74, 139].

4.4 Results of Correlations (Explicit Food Preferences)

4.4.1 Results of Correlation Between Subjective Ratings and Parotid Hemodynamics

After processing the fNIRS data, the mean value of concentrations of HbR, HbO, and HbT were calculated. Then, the mean values were used to analyze the correlations, and the results is shown in Table 4.2. Table 4.2 presents the correlation coefficients linking participants' subjective ratings ("liking" and "wanting") to mean changes in cerebral blood flow in the parotid region, measured separately for each ice cream state and ice cream color under photo and video stimulus. Hemodynamic metrics derived from fNIRS included deoxygenated hemoglobin (HbR), oxygenated hemoglobin (HbO), and total hemoglobin (HbT) on both the left and right sides of the parotid region.

Table 4.2: Correlation coefficients between subjects' ratings and the signal mean of cerebral blood flow in the parotid region

			HbR		HbO		HbT	
			left	right	left	right	left	right
Color	Liking-Photo	stimuli	0.637	0.365	-0.003	-0.672	-0.160	-0.518
		evaluate	-0.768**	0.210	-0.580	-0.825**	0.051	0.020
	Wanting-Photo	stimuli	-0.095	0.094	-0.964**	-0.549	-0.848**	-0.308
		evaluate	-0.536	0.420	0.159	0.870	-0.237	0.594
	Liking-Video	stimuli	-0.435	-0.826**	-0.566	-0.191	0.384	-0.552
		evaluate	0.466	-0.344	-0.472	0.546	-0.141	0.228
	Wanting-Video	stimuli	0.955**	-0.235	0.733**	-0.664	-0.836**	-0.603
		evaluate	-0.127	0.402	-0.477	-0.862**	-0.629	0.508
State	Liking-Photo	stimuli	0.510	0.382	0.821**	0.553	0.726**	-0.520
		evaluate	0.636	-0.733**	-0.601	-0.868**	0.177	-0.942**
	Wanting-Photo	stimuli	-0.878**	0.271	0.378	0.991**	-0.183	0.571
		evaluate	-0.831**	-0.952**	-0.350	-0.171	0.820**	-0.311
	Liking-Video	stimuli	0.957**	0.573	0.453	0.070	0.228	-0.598
		evaluate	0.430	0.537	0.778**	0.269	0.419	-0.464
	Wanting-Video	stimuli	0.076	-0.241	-0.178	-0.349	0.484	-0.174
		evaluate	0.668	0.420	-0.76**	0.597	-0.479	0.313

** : p <0.01 The number in the table refer to correlation coefficients.

Correlation Between Ratings and Cerebral Blood Flow Changes by Ice Cream Color

The correlation coefficients between subjects' ratings and the change in the signal mean of cerebral blood flow related to saliva were determined separately for each ice cream color. According to the results, when subjects were asked how happy it would be if they tasted this now in response to a photo of ice cream, no correlation was found between subjects' ratings and cerebral blood flow during stimulation. On the other hand, there was a strong negative correlation between the subject's ratings and the HbR (r = -0.768) on the left side and HbO (r = -0.825) on the right side while rating the ice cream photos. Thus, it can be said that the mean values of HbR on the left side and HbO on the right side tend to become smaller as the subject's evaluation of the ice cream increases. These results indicate that as the liking evaluation increases, deoxygenated hemoglobin (HbR) in the left hemisphere tends to decrease, while oxygenated hemoglobin (HbO) in the right hemisphere also shows a decrease. This suggests that as participants' liking ratings increase, HbR decreases on the left side, indicating heightened neural activity in the left parotid region (as increased neural activity is typically associated with a reduction in HbR). Additionally, the observed decrease in HbO on the right side, corresponding with higher ratings, suggests that oxygen supply to the right parotid region may be decreasing. In summary, the greater the happiness participants feel when viewing ice cream images, the more neural activity increases in the left parotid region, while oxygenated hemoglobin concentration decreases in the right parotid region. The findings indicate that as participants' ratings increased, there was a reduction in deoxygenated hemoglobin (HbR) on the left hemisphere and a concurrent decrease in oxygenated hemoglobin (HbO) on the right hemisphere. Generally, increased brain activity is associated with a decrease in HbR [140], suggesting heightened neural activity in the left hemisphere. Conversely, the reduction in HbO on the right side implies a decrease in oxygen supply in that region. This observation aligns with previous studies indicating the involvement of the left hemisphere in processing pleasure and positive emotions [61].

When subjects were asked how much they would like to eat the same ice cream in response to a photo of that ice cream, there was a strong negative correlation between the subject's ratings and HbO ($r = -0.964$) and HbT ($r = -0.848$) on the left side during stimulation. Thus, it can be said that the mean value of HbO and HbT on the left side tends to become smaller as the subject's evaluation of the ice cream increases. On the other hand, a strong positive correlation between the subject's ratings and HbO ($r = 0.870$) on the right side when rating photos. Therefore, it can be said that the mean values of HbO on the right become larger as the subject's evaluation of the ice cream increases. These results suggest that as the evaluation of desire increases, there is a tendency for the levels of oxygenated hemoglobin (HbO) and total hemoglobin (HbT) to decrease in the left hemisphere, indicating that oxygen consumption in this region becomes more efficient when regulating appetite. On the other hand, a strong positive correlation was observed for HbO in the right hemisphere, meaning that higher desire ratings are associated with an increase in oxygen supply to the right hemisphere. Therefore, the stronger the desire to eat the ice cream, the more blood flow decreases in the left parotid region during stimulus presentation, while neural activity increases in the right parotid region during the evaluation phase. As the degree of wanting increases, a decrease in HbO and HbT levels is observed in the left hemisphere, while an increase in HbO is noted in the right hemisphere. The reduction of HbO and HbT in the left hemisphere suggests neural activity optimization and efficient oxygen consumption [50]. Conversely, the increase of HbO in the right hemisphere may indicate heightened neural processing associated with desire in this region. This finding aligns with reports that the right hemisphere plays a significant role in emotional desires and impulsivity [141].

When subjects were asked how happy it would be if they tasted this then and there in response to a video of ice cream, a strong negative correlation was found between subjects' ratings and HbR ($r = -0.826$) on the right side during stimulation. Therefore, it can be said that the mean values of HbR on the right side tend to decrease as the subject's evaluation of the ice cream increases. On the other hand, no correlation was found between subjects' ratings and cerebral blood flow during rating the ice cream videos. The result demonstrated that the higher the liking for dynamic stimuli (videos), the more pronounced the decrease in deoxygenated hemoglobin (HbR) in the right hemisphere. This suggests that when food is presented dynamically in a video, the right side of the brain may play a more efficient role in utilizing oxygen, potentially contributing to the processing of pleasure and satisfaction. As the preference for dynamic stimuli increases, a decrease in HbR in the right hemisphere, indicating heightened neural activity, is observed. This suggests that dynamic visual stimuli, such as videos, have the potential to activate the right hemisphere's visual and emotional processing regions. It is noted that dynamic stimuli elicit stronger attention and emotional responses compared to static images [142].

When subjects were asked how much they would like this food now in response to a video of ice cream, a strong positive correlation was found between subjects' ratings and HbR ($r = 0.955$) and HbO ($r = 0.733$) on the left side during stimulation. Moreover, a strong negative correlation between the subject's ratings and the HbT ($r = -0.836$) on the subject's left side during stimulation. Thus, it can be said that the mean values of HbR and HbO on the left side tend to become larger as the subject's evaluation of the ice cream increases, and the mean values of HbT on the left side tend to become smaller as the subject's evaluation of the ice cream increases. On the other hand, there was a strong negative correlation between the subject's ratings and the HbO ($r = -0.862$) on the right side while rating the ice cream photos. Thus, it can be said that the mean values of HbO on the right side become smaller as the subject's evaluation of the ice cream increases. These results suggest that the stronger the desire to eat ice cream, the more complex hemodynamic changes occur in the left parotid region during stimulus presentation, while neural activity in the right parotid region decreases during evaluation. As desire increases, both deoxygenated hemoglobin (HbR) and oxygenated hemoglobin (HbO) in the left hemisphere also increase, indicating that the left prefrontal cortex may be involved in processing desire-related information, leading to increased oxygen supply.

Generally, increased neural activity is associated with a decrease in HbR; however, the observed increase in HbR here suggests an atypical response, possibly reflecting the complex hemodynamic reactions to dynamic video stimuli [130]. Additionally, a negative correlation was observed in total hemoglobin (HbT) in the left hemisphere, indicating that as desire increases, overall blood flow may decrease. This could imply that the brain is efficiently allocating resources to the specific task at hand.

The results indicate that emotional and desire-based evaluations in response to food stimuli trigger different hemodynamic responses across the cerebral hemispheres. The left hemisphere is primarily involved in processing positive emotions and desires [61], whereas the right hemisphere is associated with emotional information processing and impulsivity, often exhibiting strong reactions to dynamic food stimuli [66]. Additionally, the type of stimulus (e.g., photos versus videos) suggests varying patterns of brain activity, implying that the brain may optimize its information processing based on the characteristics of visual stimuli. However, some studies have reported a general increase in cerebral blood flow as food cravings intensify [143], which contrasts with the observed decrease in HbT in the left hemisphere in this study.

Correlation Between Ratings and Cerebral Blood Flow Changes by Ice Cream State

According to the results, when subjects were asked how happy it would be if they tasted this now in response to a photo of ice cream, a strong positive correlation was found between subjects' ratings and HbO (r = 0.821) and HbT (r = 0.726) on the left side during stimulation. Therefore, it can be said that the mean values of HbO and HbT on the left side tend to increase as the subject's evaluation of the ice cream increases. On the other hand, there was a strong negative correlation between the subject's ratings and the HbR (r = -0.733), HbO (r = -0.868), and HbT (r = -0.942) on the subject's right side while rating the ice cream photos. Thus, it can be said that the mean values of HbR, HbO, and HbT on the right side tend to become smaller as the subject's evaluation of the ice cream increases. When participants viewed the photo of the ice cream and responded to the question, "How happy would you be if you ate this ice cream now?", those who indicated a higher level of liking showed an increase in oxygen supply and blood flow in the left parotid region. The increase in oxygenated hemoglobin suggests heightened neural activity in the left parotid region. In contrast, in the right parotid region, hemoglobin concentration decreased as liking levels increased. The observed reduction in total hemoglobin in the right parotid region indicates a decrease in blood flow in that area, suggesting that the right hemisphere may be less active at this stage. The different correlations observed in the left and right parotid regions highlight the functional asymmetry between hemispheres in the brain's response to visual liking. The left hemisphere appears to be involved in processing emotions and rewards, reflecting an active response to higher levels of liking. Meanwhile, the decreased activity in the right hemisphere may represent a compensatory phenomenon in response to the increased activity in the left hemisphere. Previous studies have reported that left frontal lobe activity is associated with positive emotions and approach behaviors [60]. These results are consistent with prior findings suggesting that the left hemisphere is involved in the processing of positive affect and reward mechanisms. Moreover, Previous research also indicates that the left and right hemispheres engage in different types of information processing, with increased activity in one hemisphere sometimes leading to decreased activity in the other [144]. The observed decrease in right hemisphere activity may be considered a compensatory phenomenon in response to the heightened activity in the left hemisphere.

When subjects were asked how much they would like this food now in response to a photo of ice cream, there was a strong negative correlation between the subject's ratings and HbR ($r = -0.878$) on the left side and a strong positive correlation with HbO ($r = 0.991$) on the right side during stimulation. Thus, it can be said that the mean value of HbR on the left side tends to become smaller and the mean value of HbO on the right side tends to become larger as the subject's evaluation of the ice cream increases. Previous research has reported responses to reward-related stimuli in various brain regions, including the prefrontal cortex and limbic system [145]. These findings suggest that desires and motivations are processed through a complex neural network that spans both hemispheres. On the other hand, when subjects rated the stimulus pictures, there was a strong negative correlation between HbR on the left ($r = -0.831$) and right ($r = -0.952$) sides and a strong positive correlation between HbT ($r = 0.820$) on the left side. Therefore, it can be said that the mean values of HbR on the left and right sides become smaller as the subject's evaluation of the ice cream increases, but the mean value of HbT on the left side tends to increase. As the level of desire increases, the concentration of deoxygenated hemoglobin (HbR) decreases in the left parotid region. The reduction in HbR indicates an increase in oxygenation, suggesting heightened neural activity in this area. Conversely, as the level of desire increases, the concentration of oxygenated hemoglobin (HbO) increases in the right parotid region, signifying heightened neural activity in the right hemisphere. These findings suggest that both parotid regions are involved in the evaluation of desire. The decrease in HbR in the left hemisphere and the increase in HbO in the right hemisphere may reflect the involvement of a complex neural network related to the assessment of desire. This suggests that the motivational aspect of "wanting" activates multiple regions of the brain.

When subjects were asked how happy they would be if they tasted this now in response to a video of ice cream, a strong positive correlation was found between subjects' ratings and HbR ($r = 0.957$) on the left side during stimulation. Therefore, it can be said that the mean values of HbR on the left side tend to increase as the subject's evaluation of the ice cream increases. On the other hand, there was a strong positive correlation between the subject's ratings and the HbO ($r = 0.778$) on the subject's left side while rating the ice cream videos. Thus, it can be said that the mean values of HbO on the left side tend to become larger as the subject's evaluation of the ice cream increases. Generally, increased neural activity tends to result in a decrease in deoxygenated hemoglobin (HbR). However, the observed increase in HbR here might appear contradictory. Previous studies have reported that fNIRS signals may not always display typical patterns during complex cognitive tasks [146]. Dynamic video stimuli are more complex than static photo stimuli, and this could result in different hemodynamic response patterns. The increase in HbR may reflect distinct patterns of brain activity or blood flow regulation mechanisms in response to dynamic stimuli. Additionally, the observed increase in oxygenated hemoglobin (HbO) during the evaluation phase suggests that neural activity in the left parotid region persists or even intensifies after the stimulus is presented. This may indicate ongoing emotional or cognitive processing related to the stimulus as participants evaluate their liking. Therefore, video stimuli, which involve temporally changing information, likely lead to more complex sensory processing and cognitive load. As a result, the brain's hemodynamic responses to video stimuli may follow patterns different from those observed with static stimuli. In particular, the activity in the left parotid region during liking evaluations likely reflects the integration of dynamic visual information with hedonic responses.

When subjects were asked how much they would like if they could eat it in response to a video of ice cream, no correlation was found between subjects' ratings and subjects' cerebral blood flow during stimulation. However, there was a strong negative correlation between the subject's ratings and the HbO ($r = -0.760$) on the subject's left side while rating the ice cream videos. Thus, it can be said that the mean values of HbO on the left side tend to become smaller as the subject's evaluation of the ice cream increases. No correlation between desire ratings and cerebral hemodynamics during stimulus presentation suggests that dynamic video stimuli may require more complex information processing than merely triggering an immediate desire response. As a result, the timing and patterns of neural activity could differ.

On the other hand, the observed decrease in oxygenated hemoglobin (HbO) during the evaluation phase indicates that neural activity in the left parotid region decreases as desire increases. Previous research has demonstrated that dynamic visual stimuli increase cognitive load and influence the timing and patterns of brain activity [147]. Video stimuli, being more complex than static images due to the enriched temporal and spatial processing they require, can induce different hemodynamic responses as a result of their intricate cognitive and emotional processing demands. This suggests that the cognitive or emotional processes related to desire ratings may have shifted to other brain regions. Therefore, the absence of a significant correlation between desire ratings and hemodynamics during stimulus presentation, combined with the negative correlation observed in the left parotid region during evaluation, indicates that neural activity related to desire may occur in different regions or at different times in response to dynamic visual stimuli. Dynamic stimuli likely consume more of the participants' attentional and cognitive resources, which may delay or disperse the processes involved in the formation and evaluation of desire.

These results indicate that physiological responses to visual stimuli are closely related to subjective evaluations of "liking" and "wanting." Specifically, changes in blood flow in the left parotid region were strongly associated with liking evaluations, suggesting that the left hemisphere may play a significant role in processing the hedonic aspects of visual food stimuli. On the other hand, the evaluation of wanting appears to involve both hemispheres, indicating that the motivational aspects of appetite activate a broader neural network. Furthermore, the difference in physiological responses between static photo stimuli and dynamic video stimuli suggests that the nature of the stimulus influences neural processing. Video stimuli likely require more complex sensory integration and cognitive processing, resulting in distinct hemodynamic patterns.

Additionally, within the framework of the Stimulus-Organism-Response (S-O-R) model, this study demonstrated that visual stimuli (S) elicit physiological responses (O) in the organism, which are closely related to subjective evaluations (R). Specifically, visual stimuli of ice cream induced changes in cerebral blood flow in the parotid region, which were correlated with subjective evaluations such as liking and wanting. This provides a deeper understanding of the relationship between sensory input, neural activity, and behavioral intent in the context of appetite and consumption behavior.

4.4.2 Results of Correlation Between Subjective Ratings and prefrontal cortex Hemodynamics

Table 4.3: Correlation between subjects' ratings and the signal mean of cerebral blood flow in the prefrontal region by state

	Photo_Liking_HbT		Photo_Wanting_HbT		Video_Liking_HbT		Video_Wanting_HbT	
	left	right	left	right	left	right	left	right
stimuli	-0.236	-0.171	-0.137	0.036	0.977**	-0.227	0.118	0.221
evaluate	0.895**	-0.252	-0.888**	-0.193	0.515	0.729**	0.134	0.601

** : $p < 0.01$ The number in the table refer to correlation coefficients.

Table 4.3 presents correlation coefficients between participants' subjective ratings ("How happy would you be if you tasted this now?" and "How much would you like to eat this food now?") and total hemoglobin (HbT) changes in the prefrontal cortex—examined separately for static (photo) and dynamic (video) ice cream stimuli in different melting states.

When subjects were asked how happy they would be if they tasted this at that moment in response to a photo or video of ice cream, a strong positive correlation was found between subjects' ratings and HbT (r = 0.895) on the left side of the prefrontal cortex while rating the ice cream photos. Moreover, a strong positive correlation was found between subjects' ratings and HbT (r = 0.977) on the left side of the prefrontal cortex during stimulation, and a strong positive correlation was found between subjects' ratings and HbT (r = 0.729) on the right side of the prefrontal cortex while rating the ice cream videos. Thus, it can be said that the higher the subject's evaluation, the larger the mean values of HbT on the left side of the prefrontal cortex tended to be while rating the ice cream photos; the higher the subject's evaluation, the larger the mean values of HbT on the right side of the prefrontal cortex tended to be while rating the ice cream videos, and the larger the mean values of HbT on the left side of the prefrontal cortex tended to be during stimulation of the ice cream videos. On the other hand, when subjects were asked how much they would like to eat this food in response to a video of ice cream, a strong negative correlation was found between subjects' ratings and HbT (r = -0.888) on the left side of the prefrontal cortex while rating the ice cream photos. Therefore, it can be said that the higher the subject's evaluation, the smaller the mean values of HbT on the left side of the prefrontal cortex tended to be while rating the ice cream photos. Previous research has reported that activation in the left prefrontal cortex is associated with positive emotional states [60]. Thus, the result indicates an increase in HbT in the left prefrontal cortex as the "happiness" rating for ice cream images increases, align with prior research suggesting that positive emotions are linked to left prefrontal cortical activity.

When participants rated "how happy they would be" (liking) in response to ice cream photos, a strong positive correlation was observed between liking and total hemoglobin (HbT) in the left prefrontal cortex. This indicates that the higher the participants' liking ratings for the ice cream photos, the more blood flow (HbT) increased in the left prefrontal cortex. The prefrontal cortex is deeply involved in decision-making and pleasure processing, and the activation of the left side suggests that the evaluation of visual stimuli is linked to positive emotions and reward processing. In summary, the greater the happiness participants feel in response to the visual stimuli of ice cream, the more HbT increases in the left prefrontal cortex, highlighting the crucial role of the left prefrontal cortex in processing positive emotions and rewards.

Furthermore, evaluations of ice cream videos showed activation in not only the left but also the right prefrontal cortex. This suggests that dynamic video stimuli activate both sides of the prefrontal cortex more robustly when participants assess their liking for the ice cream. Particularly, blood flow increased significantly in the left prefrontal cortex during video viewing, while the right prefrontal cortex was activated during the evaluation phase. This indicates that dynamic visual stimuli engage both hemispheres of the prefrontal cortex, promoting emotional and cognitive processing simultaneously. Previous research has reported that dynamic emotional stimuli elicit activation in more extensive brain regions compared to static ones [148]. This aligns with the current findings, where video stimuli activated both the left and right prefrontal cortices. The observed bilateral prefrontal activation in response to video evaluations suggests that dynamic visual information requires more complex brain processing, potentially facilitating both emotional and cognitive processing simultaneously.

Moreover, when participants rated "how much they wanted to eat" the ice cream (wanting), a strong negative correlation was observed with HbT in the left prefrontal cortex. This suggests that as the level of desire increases, HbT in the left prefrontal cortex decreases, implying that different neural processes are triggered by appetite or impulsive desire. This phenomenon suggests that desire may be linked to emotional responses, and that when impulsive desire for food arises, prefrontal cortex activity may shift to different areas of the brain. Previous research has reported that impulsive desires for food are associated with decreased activity in the prefrontal cortex, which is linked to self-regulation [149]. This suggests that when strong cravings arise, activity in the left prefrontal cortex—responsible for self-control and inhibition—may decrease, potentially leading to a relative increase in the activity of other brain regions.

Differences in prefrontal cortex activation patterns were also observed depending on whether the stimuli were static photos or dynamic videos. In the case of photo stimuli, a positive correlation between HbT and liking was primarily observed in the left prefrontal cortex, with no clear role for the right prefrontal cortex. On the other hand, with video stimuli, both hemispheres of the prefrontal cortex were activated, especially with significant right prefrontal cortex activation during evaluation. Static photo stimuli primarily activate the left prefrontal cortex, whereas dynamic video stimuli engage both sides of the prefrontal cortex more extensively. This indicates that the more dynamic the visual information, the more brain regions become involved, suggesting that dynamic visual stimuli require more complex brain processing.

In conclusion, these results reveal that total hemoglobin (HbT) in the prefrontal cortex varies systematically with participants' subjective ratings of happiness (liking) and desire (wanting) for ice cream stimuli. Left-prefrontal increases in HbT appear more consistently tied to positive emotion and reward evaluations, particularly for static images, whereas dynamic stimuli engage bilateral prefrontal areas more extensively. Meanwhile, strong desires ("wanting") may coincide with a relative decrease in left-prefrontal blood flow, aligning with theories that impulsive eating behaviors dampen regulatory mechanisms.

4.4.3 Correlation of Cerebral Blood Flow Between Parotid and Prefrontal Regions

Table 4.4: The correlation of the signal mean change of cerebral blood flow between the parotid and prefrontal regions

		Photo_Liking_HbT		Photo_Wanting_HbT		Video_Liking_HbT		Video_Wanting_HbT	
		Left	Right	Left	Right	Left	Right	Left	Right
Color	stimuli	-0.115	0.555	-0.097	0.561	0.674	-0.483	-0.735**	-0.184
	evaluate	0.817**	-0.436	0.698	-0.552	0.355	0.844**	0.370	-0.837**
State	stimuli	0.110	-0.474	0.541	-0.227	0.409	0.843**	0.681	-0.986**
	evaluate	0.450	-0.245	-0.742**	-0.857**	-0.569	-0.077	0.323	-0.123

** : p <0.01 The number in the table refer to correlation coefficients.

Correlation of Cerebral Blood Flow Changes Between the

parotid and prefrontal regions by Ice Cream Color

The correlation coefficients between the change in the signal mean of cerebral blood flow related to saliva and the change in the signal mean of cerebral blood flow related to cognitive function were determined for each ice cream by color. Although a one-way ANOVA found no statistically significant differences among color conditions in subjective evaluations ($F(3, 64) = 0.801$, $p = 0.452$), the group means still suggest that color may be a relevant factor influencing participants' perceived liking and wanting.

When subjects were asked how happy they would be if they tasted the food in response to a photo of ice cream, a strong positive correlation ($r = 0.817$) was found between HbT on the left side of the prefrontal cortex and HbT on the left side of the parotid region during stimulation. Moreover, when subjects were asked how happy they would be if they tasted the food in response to a video of ice cream, a strong positive correlation ($r = 0.844$) was found between HbT on the right side of the prefrontal cortex and HbT on the right side of the parotid region during stimulation. Thus, it can be said that the mean values of HbT on the left side of the prefrontal cortex become larger as the mean values of HbT on the left side of the parotid region increases, and the mean values of HbT on the right side of the prefrontal cortex become larger as the mean values of HbT on the right side of the parotid region increases.

On the other hand, when subjects were asked how much they would like this food in response to a video of ice cream, a strong negative correlation ($r = -0.735$) was found between HbT on the left side of the prefrontal cortex and HbT on the left side of the parotid region during stimulation. Furthermore, there was a strong negative correlation ($r = -0.837$) between the HbT on the subject's right side of the prefrontal cortex and the HbT on the subject's right side of the parotid region while rating the ice cream videos. Therefore, it can be said that the mean values of HbT on the left and right sides of the parotid region become smaller as the mean values of HbT on the left and right sides of the prefrontal cortex increases.

The correlation between the prefrontal cortex and parotid regions showed that when participants evaluated "how happy they would be" (liking) in response to photo stimuli, a strong positive correlation was observed between HbT in the left prefrontal cortex and the left parotid region. This indicates that when viewing ice cream photos, the parotid region, which is involved in salivation, and the prefrontal cortex, which is associated with cognitive processing, are working in tandem. Specifically, as liking increased, blood flow increased in both regions, suggesting that visual stimuli related to food simultaneously trigger both physiological and cognitive processes. The prefrontal cortex is widely recognized for its role in reward processing, decision-making, and emotional regulation [150]. Notably, lateral differences have been reported, with the left prefrontal cortex associated with positive emotions and motivation, while the right prefrontal cortex is linked to negative emotions and behavioral inhibition [60]. The observed strong positive correlation between liking evaluations and activation in the left prefrontal cortex and left parotid region in response to photo stimuli suggests that positive emotions may enhance salivary secretion through activation of the left prefrontal cortex.

Similarly, for video stimuli, a positive correlation was observed, particularly between the right prefrontal cortex and the right parotid region. This suggests that dynamic visual stimuli (videos) affect both sides of the brain, with the right hemisphere showing stronger activation. Previous research has demonstrated that the right prefrontal cortex is involved in the regulation of emotional stimuli and attentional control [64] and dynamic visuals evoke stronger emotional responses compared to static images [151], suggesting that dynamic food stimuli may be linked to stronger emotional responses and the activation of the right prefrontal cortex is thought to be associated with this heightened emotional response. Furthermore, the stimulation of salivation by visual food cues is recognized as an autonomic response [21]. Furthermore, preferred food stimuli activate reward systems and evoke positive emotions [152]. The positive correlation observed during the liking evaluation in this experiment aligns with these previous studies, indicating a synchronized increase in cognitive preference and physiological salivation.

In contrast, the correlation between the prefrontal cortex and parotid regions showed a strong negative correlation between the left prefrontal cortex and the left parotid region when participants evaluated "how much they wanted to eat" (wanting) in response to video stimuli. A strong negative correlation was also observed between the right prefrontal cortex and the right parotid region. This suggests that as desire increases, there is an inverse relationship between total hemoglobin (HbT) in the prefrontal cortex and the parotid region, indicating that physiological responses and cognitive processing may be working in opposite directions. This could imply that when a desire for food arises, the brain efficiently allocates resources, adjusting cognitive processing and physiological responses accordingly. The observation of a strong negative correlation between the prefrontal cortex and the parotid gland during wanting evaluations is an intriguing phenomenon. Previous studies have indicated that wanting is associated with the dopaminergic system, playing a crucial role in reward anticipation and motivational processes [153]. The finding that increased prefrontal activation corresponds with decreased salivary secretion suggests that heightened desire may invoke cognitive control or inhibition, leading to a suppression of physiological responses. This aligns with models proposing that excessive desire necessitates self-regulation and cognitive oversight, which in turn modulates autonomic activity [149].

Additionally, these results confirm the distinct roles of the left and right hemispheres. In the left hemisphere, a strong positive correlation was observed between the left prefrontal cortex and the left parotid region during the evaluation of liking for both photo and video stimuli, but a negative correlation was found during the evaluation of wanting. This suggests that the left prefrontal cortex is primarily involved in the processing of liking, while it may play a suppressive role in the processing of wanting.

Similarly, a similar correlation pattern was observed between the right prefrontal cortex and the right parotid region, particularly during evaluations of video stimuli. The right hemisphere is strongly associated with emotional processing, and it appears that dynamic visual stimuli activate the right prefrontal cortex. The functional distinctions between the left and right hemispheres have been well-documented. The left hemisphere is commonly associated with language and logical processing, whereas the right hemisphere is linked to emotional and spatial processing [154]. The findings, where the left prefrontal cortex is implicated in liking evaluations for static stimuli (photos) and the right prefrontal cortex in dynamic stimuli (videos), suggest that the nature of the stimuli (static vs. dynamic) and the content of the evaluation may influence the differential involvement of the hemispheres.

These findings suggest a significant relationship between salivation and cognitive processing in response to food stimuli. During liking evaluations, positive emotions and reward anticipation activate the prefrontal cortex, which, in turn, promotes salivation via the autonomic nervous system. Conversely, during wanting evaluations, a strong desire may require cognitive control, leading to increased prefrontal cortex activity while potentially suppressing physiological responses. This aligns with the model where physiological responses are modulated as part of the effort to control desire [149].

Previous studies have reported associations between brain activity and subjective evaluations of food stimuli, indicating that favorable food cues enhance activity in the ventral striatum and prefrontal cortex [155]. On the other hand, some research has shown that heightened food craving corresponds with reduced prefrontal cortex activity [156], which is consistent with the negative correlation observed in the wanting evaluations of this experiment. However, other studies have reported increased prefrontal cortex activity during stronger desires [117], indicating discrepancies in findings. These differences may be attributable to factors such as the participant's hunger state, the type of stimulus used, and individual eating behavior traits.

Correlation of Cerebral Blood Flow Changes Between the parotid and prefrontal regions by Ice Cream State

The correlation coefficients between the change in the signal mean of cerebral blood flow related to saliva and the change in the signal mean of cerebral blood flow related to cognitive function were determined separately for each ice cream state. When subjects were asked how happy they would be if they tasted the food in response to a video of ice cream, a strong positive correlation ($r = 0.843$) was found between HbT on the right side of the prefrontal cortex and HbT on the right side of the parotid region during stimulation. Thus, it can be said that the mean values of HbT on the right side of the parotid region become larger as the the mean values of HbT on the right side of the prefrontal cortex increases.

On the other hand, when subjects were asked how much they would like this food at that moment in response to a photo of ice cream, a strong negative correlation was found between HbT on the left ($r = -0.742$) and right ($r = -0.857$) sides of the parotid region and HbT on the left and right sides of the prefrontal cortex while rating the ice cream photos. Furthermore, when subjects were asked how much they would like this food at that moment in response to a video of ice cream, there was a strong negative correlation ($r = -0.986$) between the HbT on the subject's right side of the parotid region and the HbT on the subject's right side of the prefrontal cortex while rating the ice cream videos. Therefore, it can be said that the mean values of HbT on the left and right sides of the parotid region become smaller as the mean values of HbT on the left and right sides of the prefrontal cortex increases, and the mean values of HbT on the right side of the parotid region become smaller as the mean values of HbT on the right side of the prefrontal cortex increases.

The correlation analysis between the prefrontal cortex and parotid region showed a strong positive correlation between HbT levels in the right prefrontal cortex and the right parotid region during the liking evaluation of ice cream videos. This suggests that as liking increases, blood flow simultaneously increases in both the right prefrontal cortex and the right parotid region. Previous research has demonstrated that the right prefrontal cortex is implicated in emotional processing and the reward system [62, 157], with its activation being associated with the experience of pleasure and satisfaction. In other words, the mechanism linking emotional evaluation and physiological response may be enhanced as liking increases. Additionally, parotid gland activity correlates with salivation and reflects physiological responses linked to food anticipation and enjoyment [21]. This robust positive correlation aligns with prior findings indicating that hedonic stimuli amplify neural activity in reward-related brain regions and elicit physiological responses associated with consumption [152]. The dynamic nature of video stimuli likely provided a more immersive and engaging experience, promoting activation of the right prefrontal cortex and enhanced salivary response.

Additionally, during the evaluation of desire for ice cream photo and video stimuli, a strong negative correlation was observed between HbT levels in the left and right prefrontal cortex and the left and right parotid gland regions. This indicates that as the desire to consume food increases, activity in the prefrontal cortex rises while blood flow related to salivation in the parotid gland decreases. The prefrontal cortex, particularly the dorsolateral prefrontal cortex, is involved in cognitive control, decision-making, and inhibitory processes [115]. The increased prefrontal cortex activity reflects the cognitive assessment and regulation of desire, suggesting the operation of self-control mechanisms that modulate impulsive eating behavior. The suppression of salivation accompanying increased desire implies that cognitive control mechanisms suppress physiological responses to maintain homeostasis and adapt to social norms [149]. This inverse relationship between cognitive control and physiological response aligns with studies indicating that heightened prefrontal cortex activity is associated with the suppression of automatic responses [116, 158].

Moreover, these results suggest different response mechanisms between the two brain hemispheres. The positive correlation observed in the right hemisphere's involvement in emotional processing during liking evaluations supports the notion that the right prefrontal cortex plays a significant role in the pleasurable experiences derived from reward stimuli [159]. In contrast, the left hemisphere's engagement and negative correlation during wanting evaluations suggest that the left prefrontal cortex may have a greater role in cognitive control and inhibitory functions [160]. However, these findings are inconsistent with some previous studies. For example, it has been reported that emotional processing involves both hemispheres, with lateralization potentially depending on the type of emotion and context [161]. Additionally, the suppression of salivary secretion as desire increases contradicts studies suggesting that anticipation of food increases salivation and salivary gland activity [19]. One possible explanation for this discrepancy is that the cognitive processes related to desire in this study might include higher-order decision-making and self-regulation, which could override automatic salivary responses.

4.5 Results of Implicit Food Preferences

4.5.1 Correlation Between Reaction Time and Photo Selections

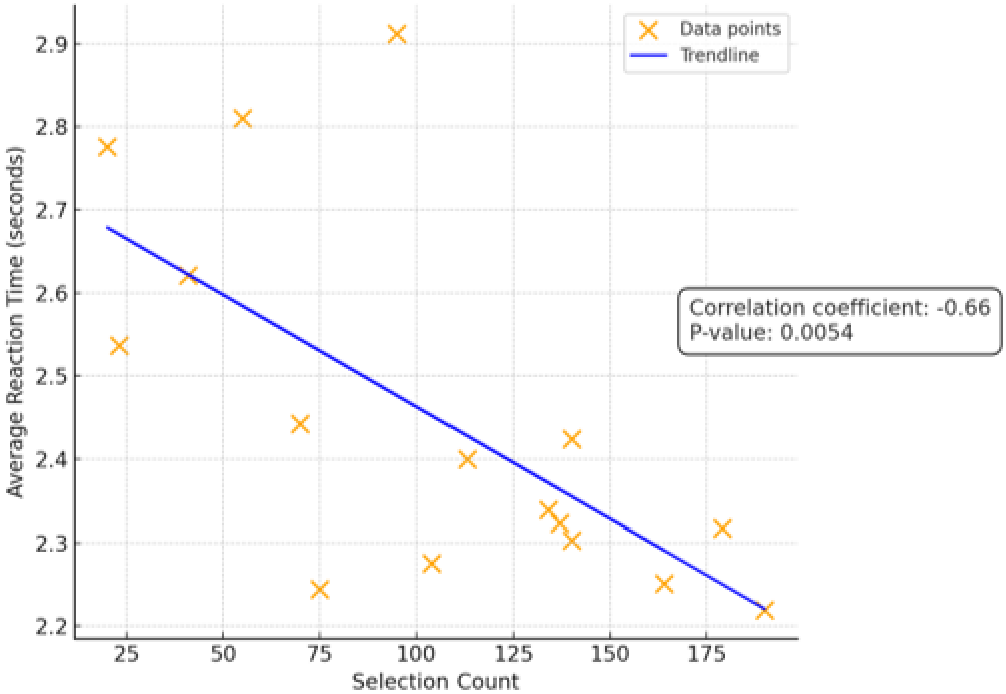

Figure 4.4: Correlation Between Selection Frequency and Reaction Time (Photo)

The figure 4.4 illustrates the relationship between the number of selections for each ice cream photo and the corresponding average reaction time. In the scatterplot, orange data points represent the pairs of selection counts and reaction times for each type of ice cream, while the blue line shows the trend line (linear regression) based on the data. Correlation analysis revealed a statistically significant negative correlation between selection count and average reaction time (correlation coefficient r = -0.66, p-value = 0.0054). This negative correlation suggests that shorter reaction times indicate a more automatic and intuitive response to stimuli, with minimal hesitation or conflict. Considering this along with the higher number of selections, it can be inferred that participants tend to respond quickly and repeatedly to stimuli they find favorable. This result demonstrates a significant negative correlation between reaction time and selection frequency when participants choose ice cream images, indicating that faster response times are associated with stronger intuitive preferences.

4.5.2 Correlation Between Reaction Time and Video Selection

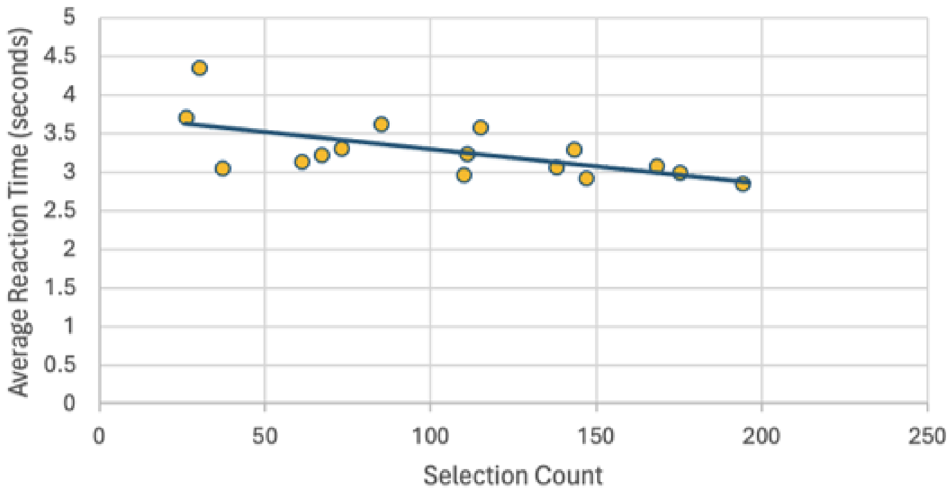

Figure 4.5: Correlation Between Reaction Time and Selection Frequency in Ice Cream Video Preferences (Video)

The figure 4.5 illustrates how selection frequency for each ice cream video stimulus relates to its average reaction time during the forced-choice task. In the scatter plot, each orange data point represents the total number of selections for a particular video, plotted against the mean time participants spent making that choice. A linear regression trend line (blue) demonstrates a negative correlation: as selection frequency rises, average reaction time decreases.

Statistical analysis confirms this inverse relationship, with a Pearson correlation of $r = -0.55$ ($p = 0.034$). These results suggest that participants who quickly select a stimulus also tend to choose it more frequently, reflecting a more automatic, intuitive decision-making process. Shorter reaction times typically indicate less conflict or hesitation, implying a stronger implicit preference for the stimulus. By consistently and swiftly choosing certain videos, participants reveal how subjective appeal and intuitive processing influence their choices.

Taken together with the findings from photo stimuli (also showing a negative correlation between reaction time and selection frequency), these results reinforce the idea that reaction time can serve as an implicit measure of preference strength. When confronted with stimuli they find appealing, participants respond faster and do so repeatedly, highlighting the interplay between affective responses and cognitive processing in preference-based choices.

4.5.3 Correlation Between Reaction Time and Selection Frequency in Ice Cream Photos and Videos

Table 4.5: Correlation Between Reaction Time and Selection Frequency in Ice Cream Photos and Videos

	Photo		Video	
	state	color	state	color
correlation	-0.939^{**}	0.363	-0.982^{**}	-0.706^{**}

**: $p < 0.01$ The number in the table refer to correlation coefficients.

Table 4.5 highlights the correlation between reaction time and selection frequency across two stimulus dimensions (state and color) for both photo and video presentations of ice cream. The analysis yielded significant inverse relationships in certain cases and revealed how presentation format (photo vs. video) and categorization type (state vs. color) can differentially influence participant responses.

An analysis of the correlation between reaction time and the number of selections revealed a statistically significant negative correlation for both photos and videos. This indicates that the shorter the reaction time, the more frequently the stimulus was selected. Specifically, in the analysis focusing on the state of the ice cream (e.g., the degree of melting), a very strong negative correlation was observed in both photos and videos. For photos (categorized by state), the correlation coefficient was $r = -0.94$, and for videos (categorized by state), the correlation coefficient was $r = -0.98$. These results suggest that as the reaction time for a particular state of ice cream decreases, the number of selections significantly increases. Namely, participants tended to respond quickly and frequently select ice cream in their preferred state.

In contrast, results for color (vanilla, matcha, chocolate, strawberry) diverged. For photo stimuli categorized by color, the correlation coefficient (r = 0.36) was not statistically significant, reflecting a lack of strong linkage between quick response times and selection behavior. Despite no significant difference emerging in subjective evaluations for color in a separate analysis, the video-based data yielded a statistically significant negative correlation (r = -0.71), indicating that participants who reacted faster to specific colors in videos also selected them more frequently. This pattern suggests that, although color did not yield a robust effect in photos, dynamic visual contexts (i.e., videos) may accentuate color-based preferences, even if these preferences did not reach statistical significance in direct ratings.

4.5.4 Correlation Between Reaction Time and Parotid Gland Blood Flow Changes (Color and State)

Table 4.6 reports the correlation coefficients between reaction time and parotid region blood flow in response to various ice cream stimuli. These stimuli were presented as photos or videos and further categorized by color and state.

Color-Categorized Stimuli

Although a separate analysis found no statistically significant difference across color conditions in participants' subjective evaluations, the correlation results in Table 4.6 suggest that color may still modulate parotid gland activity under certain conditions. When participants were asked, "How happy would you be if you ate this now?" in response to photos, a very strong negative correlation (r = -0.979) was observed between reaction time and changes in cerebral blood flow in the left parotid gland region. This finding implies that even if color-based differences did not reach statistical significance in subjective ratings, shorter reaction times for preferred colors may nonetheless evoke heightened activity in the left parotid gland.

Conversely, a strong positive correlation (r = 0.937) was observed in the right parotid gland, indicating that stronger preferences led to decreased blood flow in the right parotid gland region. This suggests that the left and right parotid glands may respond differently to visual preferences. Additionally, when participants were asked, "How much do you want to eat this ice cream right now?" strong positive correlations were observed in both the left (r = 0.982) and right (r = 0.922) parotid gland regions. Hence, despite the lack of statistically significant differences in color-based subjective evaluations, the correlation data indicate that shorter reaction times for specific colors in photo stimuli may parallel considerable changes

Table 4.6: Correlation Between Reaction Time and Parotid Gland Blood Flow Changes for Ice Cream Stimuli

		Liking_Left	Liking_Right	Wanting_Left	Wanting_Right
Color	Photo	-0.979**	0.937**	0.982**	0.922**
	Video	-0.386	-0.143	0.229	-0.306
Status	Photo	0.901**	-0.046	0.675**	0.542
	Video	0.222	0.826**	-0.735**	0.645

** : p <0.01 The number in the table refer to correlation coefficients.

in parotid blood flow.

In contrast, the results for video stimuli were different. When participants were asked, "How happy would you be if you ate this now?" no significant correlation was found between reaction time and changes in blood flow in either the left (r = -0.386) or right (r = -0.143) parotid gland regions. Similarly, no significant correlations were found when participants were asked, "How much do you want to eat this ice cream right now?" in either the left (r = 0.229) or right (r = -0.306) parotid gland regions. These null findings suggest that dynamic presentations might alter or diminish any color-related parotid response observed in photo-based analyses.

State-Categorized Stimuli

When participants were asked, "How happy would you be if you ate this now?" in response to ice cream photos, a very strong positive correlation (r = 0.901) was observed between reaction time (implicit preference) and the change in cerebral blood flow in the left parotid gland region. This suggests that the shorter the reaction time (the stronger the implicit preference), the greater the change in blood flow in the left parotid gland when viewing ice cream photos.

Similarly, when participants were asked, "How much do you want to eat this ice cream right now?" in response to ice cream photos, a positive correlation (r = 0.675) was also observed in the left parotid gland region, again indicating that a shorter reaction time (stronger implicit preference) corresponded to a greater change in blood flow.

However, the results for video stimuli presented a different pattern. When participants were asked, "How happy would you be if you ate this now?" in response to ice cream videos, no significant correlation was found between reaction time and cerebral blood flow changes in the left parotid gland region ($r = 0.222$). Conversely, a strong positive correlation ($r = 0.826$) was observed in the right parotid gland region.

Additionally, when participants were asked, "How much do you want to eat this ice cream right now?" in response to the video stimuli, a strong negative correlation ($r = -0.735$) was found in the left parotid gland region. This suggests that the quicker the response to the video stimulus, the lower the activity in the left parotid gland, indicating that video stimuli may have a different impact on brain responses related to preferences. On the other hand, a positive correlation ($r = 0.645$) was observed in the right parotid gland region, indicating potential differences in how the left and right parotid gland regions process information related to preference.

Hemispheric Differences and the Processing of Visual Stimuli

Regarding hemispheric differences in brain function, it is well established that the left and right hemispheres play distinct roles in emotion and reward processing. In particular, the left hemisphere is linked to positive emotions and approach-related behaviors, whereas the right hemisphere is more strongly associated with negative emotions and avoidance behaviors [60]. Evidence from the present study indicates that static stimuli (i.e., photos) elicit notably higher activation in the left parotid gland, which may reflect immediate evaluation of appetitive food cues.

By contrast, dynamic stimuli (i.e., videos) engage the right parotid gland more extensively, suggesting that temporal changes and complex visual information activate right-hemisphere mechanisms involved in attention and emotional processing [69]. This hemispheric divergence is consistent with observations that visual food cues can induce salivation and associated neural activity [23], yet relatively few studies have directly examined hemisphere-specific parotid responses.

Furthermore, reaction time offers an important indicator of implicit preference: shorter latencies typically denote stronger or more immediate choices [162]. The robust correlation found between left parotid activity and reaction time in response to static ice cream images suggests that intuitive reward evaluations unfold more prominently in the left hemisphere. Conversely, the weaker correlations observed for video stimuli may stem from the increased cognitive load of dynamic visuals, potentially dispersing or shifting reward-related processing to the right hemisphere.

These findings highlight how brain responses to ice cream stimuli differ depending on image format. Photos appear to intensify left parotid activation, reflecting direct preference appraisal, while videos—due to their temporal and spatial complexity—elicit stronger engagement of right parotid activity. This pattern is consistent with other research showing that static

Table 4.7: Correlation Between Reaction Time and Prefrontal Cortex Blood Flow Changes for Ice Cream Stimuli

		Liking_Left	Liking_Right	Wanting_Left	Wanting_Right
Color	Photo	0.920**	0.667**	-0.888**	-0.370
	Video	-0.523	0.991**	-0.563	-0.435
State	Photo	-0.548	-0.411	0.686**	-0.255
	Video	0.937**	0.911**	-0.351	-0.015

** : p <0.01 The number in the table refer to correlation coefficients.

food images activate orbitofrontal and amygdala circuits tied to reward [139], whereas dynamic stimuli heighten visual attention and cognitive demands, potentially diffusing reward-related activity [10]. Additionally, the parotid gland's salivary function further underscores its direct link to appetite and taste processing, as demonstrated by Pavlovian conditioning [23].

From a color-specific standpoint, photo-based stimuli elicited a pronounced left parotid response, suggesting that color cues in static images robustly trigger positive emotions and approach behaviors. In contrast, videos—though more information-rich—did not show a similarly clear association, perhaps because dynamic presentations engage different neural pathways for reward evaluation. Overall, these results point to distinct neural mechanisms for processing static versus dynamic images of food, with hemispheric involvement reflecting the nature and complexity of the visual stimulus.

4.5.5 Correlation Between Reaction Time and Prefrontal Cortex Blood Flow Changes (Color and State)

Table 4.7 reports the correlation coefficients between reaction time and Prefrontal Cortex blood flow in response to various ice cream stimuli. These stimuli were presented as photos or videos and further categorized by color and state. Specifically, the table illustrates the relationship between reaction time and cerebral blood flow changes when participants were asked, "How happy would you be if you ate this now?" and "How much do you want to eat this ice cream right now?" during forced-choice trials.

Color-Categorized Stimuli Although a separate analysis found no statistically significant differences in subjective evaluations across color conditions, the correlation patterns described below indicate that color may nonetheless influence prefrontal cortex activity under certain circumstances.

Results for Color-Based Photo Stimuli:

When participants were asked, "How happy would you be if you ate this now?" in response to photos, a very strong positive correlation ($r = 0.920$) was observed between reaction time and changes in cerebral blood flow in the left prefrontal cortex. This suggests that the shorter the reaction time (indicating stronger preference), the smaller the changes in blood flow in the left prefrontal cortex. Hence, even if color-based subjective ratings did not reach statistical significance, these findings imply that when participants have a strong preference, decision-making occurs more quickly without significant activation in the left prefrontal cortex. A similar positive correlation ($r = 0.667$) was also observed in the right prefrontal cortex, suggesting that both hemispheres exhibit a common neural response when evaluating preferences for ice cream photos.

On the other hand, when participants were asked, "How much do you want to eat this ice cream right now?" a very strong negative correlation ($r = -0.888$) was found in the left prefrontal cortex. This suggests that the shorter the reaction time, the larger the changes in blood flow, indicating that strong desires or cravings lead to increased neural activity in this region. No significant correlation was observed in the right prefrontal cortex for this question.

Results for Color-Based Video Stimuli:

In contrast, for video stimuli, when participants were asked, "How happy would you be if you ate this now?" no significant correlation was found between reaction time and cerebral blood flow in the left prefrontal cortex, but a very strong positive correlation ($r = 0.991$) was observed in the right prefrontal cortex. This indicates that for dynamic stimuli (videos), the right prefrontal cortex plays a significant role in processing preference. No significant correlation was found for the question, "How much do you want to eat this ice cream right now?" in either the left or right prefrontal cortex.

These results suggest that the type of visual stimulus (photo or video) affects how the prefrontal cortex responds to preference-related decision-making. In particular, static photo stimuli are associated with reduced blood flow in both hemispheres during quick decisions related to preference, while the left prefrontal cortex is more engaged when participants express a strong desire for the ice cream. For video stimuli, the right prefrontal cortex appears to be more active, suggesting that dynamic stimuli involve different neural mechanisms for preference evaluation.

The analysis of responses to photo stimuli revealed significant correlations when participants were asked, "How happy would you be to eat this now?" Strong positive correlations were observed in the left prefrontal cortex, and positive correlations were also found in the right prefrontal cortex. This indicates that shorter reaction times (indicating stronger liking) are associated with reduced changes in blood flow in the prefrontal cortex. The prefrontal cortex is known to be involved in decision-making and evaluation processes. When reaction times are shorter, participants may be making intuitive or automatic judgments, which involve less complex cognitive processing, potentially leading to reduced prefrontal activity. Previous studies have shown that prefrontal activity related to reward prediction errors varies depending on decision-making difficulty [163]. Reports indicate that simpler judgments result in decreased prefrontal activity, aligning with the current findings.

In contrast, when participants were asked, "How much would you want to eat this ice cream now?" a strong negative correlation was observed in the left prefrontal cortex. This suggests that shorter reaction times (indicating stronger wanting) are associated with increased blood flow changes in the prefrontal cortex. Strong desires or impulsive tendencies may increase left prefrontal activity, implying that cognitive processes related to self-control and desire inhibition are activated. Prior studies have reported that the left lateral prefrontal cortex is involved in self-regulation regarding food [116]. The increase in activity during desire suppression, although somewhat inconsistent with the current findings, can be explained within the context of decision-making involving both desire and selection.

Regarding video stimuli, a strong positive correlation was observed in the right prefrontal cortex when participants were asked, "How happy would you be to eat this now?" However, no significant correlation was found in the left prefrontal cortex. This suggests that the right prefrontal cortex may play a crucial role in the evaluation of liking for dynamic stimuli. The right prefrontal cortex is associated with visual-spatial information processing and emotional cognition. Video stimuli provide richer information than photos, potentially enhancing right prefrontal activity. Previous research by Spencer et al. reported dominance in right-hemispheric activity in response to dynamic visual stimuli [164], supporting the increase in right prefrontal activity observed with video stimuli. In contrast, no significant correlations were found in either prefrontal cortex when participants were asked, "How much would you want to eat this ice cream now?" This implies that the evaluation of wanting for video stimuli may be processed in brain regions other than the prefrontal cortex (e.g., ventral striatum or amygdala). Sescousse et al. indicated that the desire for primary rewards (such as food) is processed more in the reward system rather than the prefrontal cortex [165].

When considering differences in brain activity based on the type of stimulus, distinct activation patterns in the prefrontal cortex were observed for photos and videos. Static photos engaged the left prefrontal cortex more prominently, while dynamic videos involved the right prefrontal cortex. Moreover, differences in brain activity based on the type of question (liking versus wanting) suggest that liking and wanting involve different cognitive processes. The engagement of the right prefrontal cortex in response to dynamic stimuli aligns with previous studies. Additionally, the observed relationship between faster reactions and decreased prefrontal activity is consistent with some prior research. The increase in left prefrontal activity during strong desire appears inconsistent with certain studies on self-regulation, which may be attributable to task characteristics or individual participant differences.

State-Categorized Stimuli

When participants were asked, "How happy would you be if you ate this now?" in response to photos, no significant correlation was observed between reaction time and changes in cerebral blood flow in either the left (r = -0.548) or right (r = -0.411) prefrontal cortex. This suggests that the visual evaluation of the ice cream's state did not clearly affect the changes in cerebral blood flow related to preference strength in the prefrontal cortex. However, when asked, "How much do you want to eat this ice cream right now?" a positive correlation (r = 0.686) was observed in the left prefrontal cortex. This suggests that the shorter the reaction time (indicating a stronger preference), the smaller the change in blood flow in the left prefrontal cortex. This implies that rapid decision-making related to preference might reduce activity in the left prefrontal cortex. Moreover, no significant correlation was observed in the right prefrontal cortex (r = -0.255), indicating no observable neural response to preference in that region.

For video stimuli, when participants were asked, "How happy would you be if you ate this now?" a very strong positive correlation was observed in both the left (r = 0.937) and right (r = 0.911) prefrontal cortex. This suggests that the shorter the reaction time (indicating a stronger preference), the smaller the changes in blood flow in both prefrontal cortices, implying a consistent reduction in prefrontal activity during dynamic visual stimuli related to preference. However, when asked, "How much do you want to eat this ice cream right now?" no significant correlation was observed between reaction time and cerebral blood flow in either the left (r = -0.351) or right (r = -0.015) prefrontal cortex. This suggests that video stimuli may not elicit a clear neural response associated with preference evaluation, as was observed with photo stimuli.

These findings indicate that the brain's response to visual stimuli of ice cream based on its state differs between static photos and dynamic videos. Specifically, photo stimuli are associated with changes in cerebral blood flow in the left prefrontal cortex during rapid decision-making related to preference, suggesting reduced activity in this region. In contrast, video stimuli showed strong positive correlations in both prefrontal cortices, indicating reduced activity in both regions when preferences are formed quickly. These results highlight the differing neural mechanisms engaged by static and dynamic visual stimuli during preference evaluation.

In the results for static photo stimuli, there was no significant correlation observed between reaction times and cerebral blood flow changes in the left and right prefrontal cortices when participants were asked, "How happy would you be if you ate this now?" This suggests that visual evaluations based on the state of the ice cream did not have a clear impact on changes in prefrontal activity associated with liking intensity. Conversely, when asked, "How much do you want to eat this ice cream now?" a positive correlation was observed in the left prefrontal cortex. This indicates that shorter reaction times (indicative of stronger liking) were associated with smaller changes in blood flow in the left prefrontal cortex. This finding suggests that rapid decision-making may reduce activity in the left prefrontal cortex, aligning with prior research indicating reduced prefrontal activation during automated decision processes. For instance, Poldrack et al. demonstrated decreased prefrontal activity during habitual tasks that shift toward more automatic processing [166]. Additionally, reports by McClure et al. highlight that the left prefrontal cortex is involved in processing information related to immediate rewards or pleasure [167]. Therefore, a strong desire to eat ice cream "now" may correlate with decreased activity in the left prefrontal cortex.

For dynamic video stimuli, significant positive correlations were observed in both the left and right prefrontal cortices when participants were asked, "How happy would you be if you ate this now?" This indicates that shorter reaction times corresponded to smaller changes in blood flow, suggesting that the formation of preference occurs with reduced prefrontal activity when decisions are made quickly. Previous studies suggest that dynamic stimuli may evoke more intuitive and automatic responses compared to static stimuli. Bartels and Zeki reported that dynamic visual stimuli activate more extensive brain regions compared to static images but also noted decreased prefrontal activity during skilled or automated processing [168]. However, when participants were asked, "How much do you want to eat this ice cream now?" no significant correlations were observed, suggesting that video stimuli may not trigger distinct neural responses related to liking evaluations.

From the perspective of functional differentiation between the left and right prefrontal cortices, significant correlations were found only in the left prefrontal cortex for static stimuli, while strong correlations were observed in both cortices for video stimuli. This aligns with previous research indicating that the left prefrontal cortex is associated with linguistic and analytical processing, while the right prefrontal cortex is involved in spatial and holistic processing [60]. Video stimuli, which require the integration of temporal and spatial information, may have engaged both prefrontal cortices.

In terms of the relationship between reaction time and brain activity, findings that shorter reaction times were associated with reduced prefrontal activity suggest that cognitive load in the prefrontal cortex decreases when decision-making is rapid and automatic. Krajbich et al. showed that decision speed is linked to decision-making processes based on value [169].

The results indicate differences in prefrontal cortex activity during liking evaluations of static photos versus dynamic videos. Notably, prefrontal activity tends to decrease during rapid decision-making, potentially associated with automated processing or habitual responses. When compared with previous studies, these findings show partial alignment, underscoring the need for further research.

4.5.6 Summary of the results

Building upon the Stimulus–Organism–Response (S-O-R) model within the biometrics field, this study utilized functional near-infrared spectroscopy (fNIRS) to investigate how visual food stimuli influence appetite-related behavior. Specifically, various ice cream melting stages and color presentations were examined to uncover their effects on cerebral blood flow associated with salivary secretion and cognitive processes tied to eating behavior. By integrating both explicit evaluations (e.g., participants' self-reported "liking" and "wanting") and implicit indicators (e.g., reaction times), the research provides new insights into the neuro-mechanisms that underpin appetite and decision-making.

4.5.6.1 Summary of subjective evaluation results

Overall, the data strongly suggest that visual cues, including melting state and color, significantly shape consumers' subjective evaluations of ice cream. The intact appearance of early melting stages yields consistently higher liking and wanting scores, while the more disintegrated forms induce a noticeable decline in perceived desirability. Although a separate analysis revealed no statistically significant differences among color conditions in participants' subjective ratings, the observed patterns of means and other experimental findings suggest that color may still influence preference, as warmer, brighter hues often received more favorable evaluations relative to darker or more neutral tones. The potential for videos to accentuate sensory cues may further refine or elevate these preferences, providing valuable insights for food marketing and product presentation strategies. By highlighting the importance of visual integrity and color, these findings contribute to an evolving body of literature on how multisensory perception and cognitive expectations interact to form food preferences.

The findings reveal that preferences for food are associated with the physical state and color of visual stimuli, leading to differential activation of specific brain regions. Notably, static stimuli (photos) of ice cream increased neural activity in the left prefrontal cortex during wanting evaluations, suggesting this region's critical role in processing anticipatory aspects of food. Conversely, dynamic stimuli (videos) heightened activity in the right prefrontal cortex during liking evaluations, indicating that time-based visual stimuli activate areas associated with joy and emotional processing.

4.5.6.2 Parotid Region (Salivary Response) and Visual Food Stimuli

State-Dependent Activation:

Early vs. Fully Melted Ice Cream (Photos): When participants viewed still images of minimally melted (State 1) or nearly liquefied (State 4) ice cream, left parotid region activity tended to increase under "liking" evaluations, indicating that both extremes (solid and very melted) can modulate appetite-related neural pathways.

Rapidly Melting Ice Cream (Videos): Dynamic cues at intermediate melting states (State 2) elicited heightened blood flow in the right parotid region, suggesting that partially softened ice cream may visually strike a balance between appealing readiness to eat and structural integrity.

Color Effects:

Warmer or Brighter Colors (e.g., Strawberry Pink, Vanilla White) triggered more pronounced salivary-related activity, often in the right parotid region. On the other hand, Less Typical or Darker Colors (e.g., Green, Chocolate Brown) activated the left or right parotid side depending on whether the participant was assessing "liking" or "wanting," signifying color-based shifts in appetite and reward perception.

Photo vs. Video:

Static Images often increased left parotid responses for "wanting," reflecting how still visuals can drive anticipatory desire. On the other hand, Dynamic Videos engaged the right parotid region, especially during "liking," suggesting that time-based changes (melting, motion) strengthen emotional and salivary responses.

4.5.6.3 Prefrontal Cortex (Cognitive and Emotional Processing)

Hemispheric Specialization:

Left Prefrontal Cortex: Primarily associated with "wanting," or goal-directed motivational states. Photos of partially melted ice cream (States 2, 4) amplified left prefrontal activity, implying that transitional visual cues heighten the appetite-driving dimension of consumption.

Right Prefrontal Cortex: More closely tied to "liking," or emotional pleasure. Videos of ice cream, notably in rapidly melting states, increased right prefrontal activation, underscoring how dynamic stimuli evoke stronger affective responses.

Static vs. Dynamic Influences:

Static Images: Elevated left prefrontal engagement when participants rated how much they desired the intact or partially melted ice cream, consistent with anticipatory or approach-oriented states.

Videos: Induced bilateral (left and right) prefrontal engagement but generally highlighted the right side for "liking." This aligns with theories that motion intensifies emotional processing, particularly within the right hemisphere.

4.5.6.4 Correlations Between Subjective Ratings and Hemodynamics

Liking (Happiness):

Higher "liking" ratings typically correlated with decreases in deoxygenated hemoglobin (HbR) on the hemisphere most involved (left for photos, right for videos), implying heightened neural activity. Moreover, in some conditions (especially with dynamic stimuli), an increase in oxygenated hemoglobin (HbO) on the opposite hemisphere suggested more complex cross-hemispheric interactions.

Wanting (Desire):

Elevated "wanting" frequently led to increased left-hemisphere activity, reflecting motivational or goal-oriented processing. In contrast, the right hemisphere often showed varied responses: sometimes a decrease in certain hemoglobin signals (HbT, HbO) or a negative correlation, hinting at possible self-regulation or contextual processing.

4.5.6.5 Interplay Between Parotid and Prefrontal Activation

Positive Correlations:

During "liking" evaluations, increased blood flow in the prefrontal cortex tended to correlate positively with parotid activation on the same hemisphere (left with photos, right with videos). This suggests synchronized cognitive-affective processing, where emotional appeal and salivary readiness go hand in hand.

Negative Correlations:

For "wanting," higher prefrontal activity sometimes coincided with reduced parotid activation. This pattern may reflect cognitive control mechanisms (e.g., regulating impulsivity) that modulate salivary responses when the desire to eat is high.

4.5.6.6 Reaction Time as an Indicator of Implicit Preference(Implicit Food Preferences)

Negative Correlation with Selection Frequency:

Photos: A statistically significant inverse relationship emerged between average reaction time and number of selections. Participants who chose certain ice cream photos more frequently did so more quickly, indicating stronger, more automatic preferences.

Videos: The same negative correlation pattern held for ice cream videos. Rapid decision-making again denoted a clear, intuitive preference for certain video stimuli over others.

Interpretation:

Intuitive vs. Deliberative: Fast responses suggest intuitive choices with minimal hesitation, while slower responses indicate potential deliberation or conflict.

4.5.6.7 Influence of Ice Cream State and Color on Reaction Times

State-Based Categories:

Stronger Negative Correlation: For both static images and videos, the more preferred (and thus more frequently chosen) melting state (e.g., partially melted, fully intact) consistently yielded shorter reaction times. This indicates that state (degree of melting) is a potent driver of preference.

Color-Based Categories:

Photos: The correlation with reaction time was not significant, suggesting that color alone did not strongly affect quick selection in static images.

Videos: A notable negative correlation emerged, implying that dynamic color cues (e.g., pink or chocolate ice cream in motion) may heighten preference clarity, leading to faster and more repeated selections.

Interpretation:

State Dominance: Visual cues pertaining to structure (solid vs. melted) appear highly salient and are processed quickly, especially for photos.

Dynamic Color: In videos, color transformations (or color combined with melting cues) might engage attention more effectively, enhancing preference clarity and accelerating choice.

4.5.6.8 Correlations with Parotid Gland Blood Flow (Salivary Responses)

Photos vs. Videos: Color Classification:

Photos: Shorter reaction times (stronger preference) correlated strongly with increased blood flow changes in one hemisphere (left side for "liking," right side for "wanting") and decreased in the other, hinting at lateralized salivary responses to color.

Videos: No significant correlations emerged between reaction time and parotid flow changes when stimuli were categorized by color—suggesting that dynamic color cues might be more cognitively complex or overshadowed by motion.

Photos vs. Videos: State Classification:

Photos: More favorable states (e.g., partially melted or completely solid) elicited shorter reaction times and correlated with increased blood flow in the left parotid region, implying that the left hemisphere may be more responsive to static visual cues.

Videos: Dynamic melting states triggered heightened right parotid region activity in strongly preferred conditions, indicating right-hemisphere involvement in processing time-dependent stimuli.

Interpretation:

Hemispheric Specialization: Left-parotid region typically connects to approach-based, immediate evaluations (especially for static cues), while the right side is more attuned to emotional or global processing, often amplified by dynamic or time-based visuals.

4.5.6.9 Correlations with Prefrontal Cortex Activity

Photos (Color vs. State):

"Liking" vs. Reaction Time: Rapid responses (stronger liking) frequently coincided with lower left-prefrontal blood flow, implying reduced cognitive load for highly appealing static images.

“Wanting” vs. Reaction Time: In some cases (e.g., color-based photos), a negative correlation emerged, suggesting that high desire may engage more cortical resources, yet reduce reaction times due to immediate attraction.

Videos (Color vs. State):

Right Prefrontal Cortex: Strong positive correlation emerged for “liking” in the right PFC, especially with dynamic color stimuli, suggesting heightened emotional or holistic processing for motion-based cues.

Mixed Findings for “Wanting”: No consistent patterns were observed, implying that “wanting” in video contexts may engage additional brain regions (e.g., limbic structures) rather than the prefrontal cortex alone.

Interpretation:

Static vs. Dynamic: Photos seem to intensify left-prefrontal processing for desire (wanting), while videos prompt more right-prefrontal engagement for hedonic pleasure (liking).

Cognitive Load: Rapid decisions for strongly liked/wanted ice cream were often linked with reduced prefrontal activity, implying an intuitive rather than deliberative response.

Chapter 5

Discussion

This study investigated the impact of visual food stimuli on appetite-related behaviors within the framework of the Stimulus-Organism-Response (SOR) model, utilizing functional near-infrared spectroscopy (fNIRS) as a physiological indicator. Specifically, we conducted a detailed analysis of how visual cues such as the melting state and color of ice cream influence hemodynamic responses in the prefrontal cortex and parotid regions, subjective evaluations (Liking and Wanting), and reaction times (implicit preferences).

5.1 Discussion of Color and State in Subjective Food Evaluations ("Liking" and "Wanting")

Visual cues—including color and physical state—are powerful determinants of how individuals evaluate foods in terms of both "liking" (the hedonic pleasure) and "wanting" (the motivational drive to consume). In this study, we examined subjective ratings under various color categories (Vanilla White, Green, Strawberry Pink, and Chocolate Brown) and melting states (State 1 through State 4), presented as both static photos and dynamic videos. The findings consistently highlighted the role of visual integrity (i.e., how intact the ice cream remains) and hue (particularly bright or warm tones) in driving consumer appetitive responses. Moreover, the study's results both converge with existing literature (e.g., on the importance of visual appearance [4]) and present new insights on the interplay between food color, melting progress, and modern presentation formats (e.g., videos).

5.1.1 Effect of Food Color on "Liking" and "Wanting"

Although a separate analysis indicated that color-based differences in participants' subjective ratings did not reach statistical significance, the patterns described below suggest that color still influenced perceived liking and wanting in notable ways. The results show distinctive patterns in subjective ratings when ice cream is categorized by color (Vanilla White, Green, Strawberry Pink, and Chocolate Brown). Notably, Strawberry Pink consistently received the highest mean ratings across both photos and videos, whereas Chocolate Brown tended to rank at the lowest end. Vanilla White and Green typically occupied moderate positions, although Green at times surpassed Vanilla White in several measures.

Strawberry Pink and Positive Emotional Responses:

Across both photos and videos, Strawberry Pink emerged as the top-scoring color in "liking" ("How happy would you be if you ate this?") and "wanting" ("How much would you like to eat this now?"). This outcome resonates with research showing that warm or bright colors evoke positive affective states and boost the perceived sweetness or attractiveness of a food product [170]. Specifically, pink hues can be associated with freshness, fruitiness, and excitement [171], thus heightening both hedonic pleasure and consumption desire [172].

Lower Evaluations for Chocolate Brown:

By contrast, Chocolate Brown consistently received the lowest ratings. While chocolate is familiar and often well-liked in taste, the dark hue here may have been perceived as heavy or less visually appealing, leading to lower immediate "liking" or "wanting." Past studies suggest that darker colors can connote fullness or satiety, which might reduce appetite [173,174]. This phenomenon showcases how visual color cues can override or at least complicate taste expectations, especially in the absence of actual taste [2,175].

Moderating Effects of Vanilla White and Green:

Vanilla White and Green occupied intermediate positions, although Green occasionally outperformed White. One explanation aligns with cultural or personal associations: green might evoke novelty or perceptions of freshness (e.g., matcha, mint), while white implies a more neutral flavor profile. Studies indicate that less conventional colors can sometimes spark curiosity or higher "wanting," but only if they remain within a generally acceptable hue range [176, 177]. In the present study, Green's occasional advantage might thus reflect participants' interest in trying an uncommon but still appetizing color.

5.1.2 Effect of Ice Cream's State on Subjective Ratings

A similar yet more pronounced trend emerges when comparing melting states (State 1 through State 4). Participants awarded substantially higher ratings to ice cream that appeared fresh and intact (State 1), while progressive melting (States 2–4) led to a marked decline in both "liking" and "wanting." In particular, State 4 (significantly melted) registered the lowest ratings, often dipping into single digits. Such findings underscore the psychological impact of visual integrity: as the ice cream's structure deteriorates, participants appear less motivated to consume it.

Significance of Visual Integrity:

Similar to color, melting state profoundly shaped subjective ratings. State 1 (hard, intact ice cream) garnered the highest "liking" and "wanting," while State 4 (fully melted) elicited markedly lower evaluations—often reaching single digits. These data underscore how visual integrity (e.g., recognizable shape, solid texture) reinforces positive expectations and consumer approach [178–180]. Melted or "deteriorated" ice cream, conversely, may introduce connotations of staleness, messiness, or reduced freshness, triggering aversive reactions [181, 182].

Consistency With Previous Research:

The negative impact of advanced melting aligns with existing literature showing that people strongly prefer foods that appear visually "fresh" and structurally intact [183]. Wang and Somogyi further emphasize that external deterioration hampers both hedonic appreciation and consumption intent [180]. Likewise, the concept of sensory-specific satiety underlines that varied or visually appealing foods maintain interest longer, whereas uniform or "spoiled" appearances accelerate satiety or disinterest [184, 185].

New Observations in the Current Study:

While the substantial drop in ratings from State 2 (partially melted) to State 4 is broadly consistent with prior work, participants' mild acceptance of State 2 under certain conditions (particularly with well-liked colors like Strawberry Pink) may reflect a tolerance for modest melting so long as the ice cream appears "ready-to-eat" rather than "fully liquefied." This nuance suggests that some participants may appreciate a semi-soft state for easy consumption—an aspect that earlier, more generalized studies have not always captured.

5.1.3 Photo Versus Video: Subtle Effects on Ratings

Although the preference hierarchy (most to least favored color or state) remained broadly consistent between static photos and dynamic videos, the video format sometimes boosted ratings—especially for flavors like Strawberry Pink. Such an effect aligns with literature indicating that dynamic or motion-rich presentations can magnify emotional engagement and sensory realism, thereby nudging participants to report higher "liking" or "wanting" [176, 186]. The temporal dimension in videos (e.g., seeing the ice cream slightly melt or glisten) may reinforce perceptions of freshness and immediacy, especially for already well-liked colors or states.

Conversely, for flavors and states already perceived as less desirable (e.g., Chocolate Brown, heavily melted states), the dynamic format did not substantially elevate their ratings. This implies that visual motion can strengthen the appeal of an already-attractive option but might not fully compensate for negative impressions tied to specific color cues or excessive melting.

Overall, as the principal findings, warm, bright hues reliably maximize "liking" and "wanting," whereas darker or atypical colors reduce immediate appeal. Structurally intact ice cream (State 1) produces the highest hedonic and motivational evaluations, while fully melted forms (State 4) register the lowest. Intermediate states show variable acceptance, contingent on participants' tolerance for mild melting. Dynamic videos can amplify positive impressions for already well-liked color–state combinations but do not rescue inherently low-rated stimuli.

The strong preference for fresh-looking foods and bright colors agrees with abundant evidence that visual cues significantly steer food choice [4]. Moreover, our data highlight that mild melting may still be acceptable (especially for popular colors), refining existing models that treat any meltdown as unequivocally negative [182].

While prior research often isolates color or texture, our integrative approach shows that a partially melted state can remain appealing if paired with a well-liked hue (e.g., pink). The observed boost in ratings for dynamic presentations clarifies how time-based visual transformations can intensify existing positive biases but seldom reverse negative ones.

5.2 Applicability of fNIRS Technology in Investigating the Internal Structure of the SOR Model

In consumer and behavioral research, the Stimulus–Organism–Response (SOR) model provides a conceptual framework linking external stimuli (S) to internal states (O) and subsequent behavioral responses (R). Traditionally, researchers rely on self-reports and observed behavior to infer the "Organism" component—an often "black box" of cognitive and emotional processes. By employing functional Near-Infrared Spectroscopy (fNIRS), we aim to directly measure neural and physiological correlates of these internal states, thus offering a richer view of how stimuli shape organismic responses and eventual behaviors.

This study used visual ice cream stimuli (both static photos and dynamic videos) as the "Stimulus," while cerebral blood flow changes in the prefrontal cortex and parotid gland indexed the "Response." The intervening "Organism" processes—spanning cognitive evaluation, emotional engagement, and autonomic readiness—were inferred from both subjective evaluations ("liking," "wanting") and objective neurophysiological signals captured by fNIRS. Our findings validate fNIRS technology as a powerful tool for investigating internal structures within the SOR model and highlight several new insights regarding hemispheric specialization and salivary engagement in response to appetitive cues.

By employing fNIRS to observe hemispheric and autonomic engagement in parotid and prefrontal regions, this study illuminates how and why different forms of ice cream stimuli (color, melting state, static vs. dynamic) evoke specific neural and physiological responses. The Stimulus–Organism–Response model benefits from direct neurological data showing how emotional and motivational pathways operate, particularly highlighting right–left hemispheric asymmetries for "liking" and "wanting" under dynamic vs. static stimuli. Consequently, we confirm fNIRS as a versatile, effective technology for probing the internal structures of SOR processes: bridging subjective experiences, objective brain measurements, and salivary readiness for consumption. In so doing, we provide new insights on how visual food cues not only shape conscious evaluations but also orchestrate underlying reward mechanisms pivotal for appetite, consumer choice, and broader human behavior.

5.2.1 Effects of Visual Stimuli on Parotid and Prefrontal Cortex Activity Bridging the SOR Model

Parotid Region: Salivary Responses and Hemispheric Engagement:

State and Color as Salivary Triggers: Our findings reveal that dynamic videos of ice cream, particularly in rapidly melting or fully melted states, elicited significant blood flow increases in the right parotid region. This right-lateralized response aligns with prior research indicating that emotional or globally processed stimuli often activate right-hemisphere salivary circuits, a pattern consistent with the "Organism" component of the Stimulus–Organism–Response (SOR) model [24,131]. These results highlight the dynamic interplay between visual stimuli and salivary responses, underscoring how time-based visual changes intensify physiological readiness for consumption. Although a separate analysis found no statistically significant differences across color conditions in participants' subjective ratings, the group means and parotid responses described here suggest that color can still influence salivary readiness, particularly for certain hues and melting states.

Asymmetric Salivary Responses: Distinct patterns of hemispheric salivary engagement emerged based on ice cream color. Vanilla White primarily activated the right parotid region during "liking," likely reflecting its associations with freshness and sweetness. Strawberry Pink, by contrast, elicited more bilateral engagement, suggesting heightened emotional and motivational salience. Chocolate Brown maintained a right parotid emphasis, indicating the emotional weight often associated with darker hues, while Green predominantly engaged the left parotid region, reflecting a shift toward detailed and evaluative processes. These asymmetric responses illustrate that visual characteristics such as color and state serve as explicit stimuli ("S") in the SOR model, while hemispheric salivary readiness constitutes a critical aspect of the internal organismic response ("O").

Advancing Our Understanding of the SOR Model: By directly measuring salivary-related brain activity using fNIRS, this study advances our understanding of the SOR model by quantitatively mapping internal physiological states ("O") onto explicit external stimuli ("S"). The observed neural pathways for salivary readiness reflect distinct mechanisms for "liking" versus "wanting," offering empirical depth to the traditionally inferred processes within the SOR framework. This approach not only validates the integration of neural and physiological measures in studying appetite but also enhances the granularity of how visual food cues elicit organismic responses and influence behavioral outcomes.

Prefrontal Cortex: Hemispheric Specialization for "Liking" and "Wanting":

Static vs. Dynamic Stimuli: The prefrontal cortex exhibited distinct hemispheric activations depending on the type of stimulus and subjective response. For static photos, partially melted ice cream (States 2 and 4) significantly engaged the left prefrontal cortex during "wanting," indicating reward anticipation and goal-directed behavior [56,136]. In contrast, dynamic videos of rapidly melting ice cream (State 2) predominantly activated the right prefrontal cortex during "liking," aligning with the right hemisphere's established role in affective processing. Additionally, intact ice cream (State 1) presented dynamically elicited pronounced left-prefrontal activation during "wanting," reflecting approach-oriented cognitive engagement tied to the anticipation of consumption.

Color-Based Activation: Color further modulated prefrontal activity, with warmer and brighter hues, such as Strawberry Pink, amplifying right-prefrontal involvement, particularly under dynamic conditions. This enhanced activation suggests that color intensifies hedonic responses by engaging affective and reward circuits, providing further evidence for the brain's integration of emotionally charged visual cues. Even though no statistically significant color differences emerged in participants' subjective evaluations, these patterns of right-prefrontal activity underscore color's potential role in shaping emotional engagement—especially when combined with motion-based cues. The heightened right-prefrontal response underlines the capacity of dynamic, vibrant stimuli to evoke strong emotional engagement, reinforcing their role within the Organism component of the Stimulus–Organism–Response (SOR) model.

SOR Model in Action: Our findings illustrate the SOR model in practice, with the "Organism" (O) encompassing both cognitive (reward prediction, approach motivation) and emotional (affect processing) circuits in the prefrontal cortex. The observed hemispheric specializations highlight the left hemisphere's role in approach-driven motivations and the right hemisphere's sensitivity to emotional or complex dynamic stimuli. Visual cues (S) such as color and melting state activate prefrontal reward or emotional circuits (O), which subsequently influence physiological responses like salivation or behavioral outputs (R). These results demonstrate how the prefrontal cortex orchestrates the integration of cognitive and emotional elements in response to appetitive visual stimuli.

5.2.2 Applicability of fNIRS in Unpacking the SOR Model

fNIRS as a Tool for Sensory Brain Assessment:

Direct Measurement of Organism Processes: Traditional Stimulus–Organism–Response (SOR) research often relies on subjective self-reports or behavioral observations to infer the internal "Organism" processes. By employing functional Near-Infrared Spectroscopy (fNIRS), this study provides a direct measurement of cerebral blood flow linked to reward processing, salivation, and emotional engagement, operationalizing the organismic state in a quantifiable and objective manner. This approach moves beyond proxy indicators, allowing for precise insights into the neural and physiological underpinnings of consumer responses to appetitive stimuli.

Laboratory Validity: In a controlled block-design experiment, participants viewed static and dynamic ice cream stimuli and provided subjective "liking" and "wanting" ratings. Simultaneously, fNIRS recorded hemodynamic changes in the prefrontal cortex and parotid regions. The observed alignment between subjective ratings and fNIRS-derived data validates this technology as a robust tool for studying sensory and emotional responses in laboratory and real-world settings. These findings complement prior studies demonstrating the utility of fNIRS in consumer and marketing research [187, 188], reinforcing its capacity to bridge subjective experiences with objective neural activity.

Enhancing SOR's Internal Structure: The SOR model traditionally conceptualizes the "Organism" as a black box, mediating external stimuli and behavioral responses. fNIRS-based methods offer a means to illuminate this internal structure by identifying specific hemispheric, autonomic, and reward-related circuits engaged during stimulus processing. This study's findings, including hemispheric differences in the prefrontal (left vs. right) and parotid (left vs. right) regions, demonstrate how fNIRS can reveal the divergence or convergence of emotional and motivational states within the brain. By enriching the SOR framework with direct neurophysiological evidence, fNIRS advances our understanding of how sensory stimuli influence both cognitive and physiological components of consumer behavior.

Comparison with previous studies:

Consistent with previous studies, our findings demonstrate a strong correlation between subjective ratings (Stimulus, S) and objective hemodynamic responses (Organism, O) [4, 21]. Bright or pleasant visual stimuli elicited stronger reward-related signals, reinforcing existing theories on the emotional impact of color and its role in amplifying appetitive responses. Furthermore, our use of a block-design experiment with sequential subjective ratings aligns with established methodologies, validating fNIRS as a reliable tool for measuring cortical activation in response to external sensory stimuli [36].

Building on prior research, this study highlights the unique influence of time-based stimuli, such as melting and motion, on neural and physiological activity. Unlike static images, dynamic stimuli were shown to shift parotid and prefrontal activity from left to right hemisphere, refining the conventional understanding of hemispheric engagement and revealing that dynamic cues activate distinct or additional neural circuits. Furthermore, by linking prefrontal hemodynamic responses with parotid region activity, our findings clarify how cognitive and autonomic processes jointly respond to visual cues within the SOR framework, offering a more integrated understanding of how emotional and motivational states converge in response to appetitive stimuli.

5.3 Relationship Between Objective and Subjective Measures

In this study, we investigated the relationships between subjective evaluations of ice cream ("liking," "wanting") and objective measures derived from functional near-infrared spectroscopy (fNIRS) in the parotid gland (salivary response) and prefrontal cortex (cognitive-emotional activity). By incorporating both subjective self-reports and objective neurophysiological assessments, we aimed to capture a holistic picture of how visual cues—color, melting state, static vs. dynamic presentation—affect food preference and appetite-related processes. Our results reveal a significant correlation between subjective (participants' explicit ratings) and objective (cerebral blood flow signals), underscoring that both forms of measurement offer complementary insights into eating behavior and decision-making. Although a separate analysis showed that color-based differences in subjective ratings did not reach statistical significance, the convergence between subjective reports and parotid/prefrontal activity suggests that color may still play a nuanced role, potentially detectable through physiological measures even if not reflected in direct self-assessments.

Our results highlights how subjective food evaluations and objective fNIRS measures of parotid and prefrontal activity cohere yet illuminate different angles of appetite and preference formation. The significant correlations found between explicit ratings ("liking," "wanting") and physiological signals underscore that emotionally potent food stimuli reliably induce both conscious and unconscious appetitive responses. While these findings confirm prevailing views on hemispheric specialization and subjective–objective convergence, they also offer new nuances about dynamic vs. static presentations and about the interplay of desire and regulation. By merging subjective and objective measures, we gain a more holistic lens on the neural and behavioral drivers of eating behavior—an understanding crucial for interventions, marketing strategies, and further research into the intricate tapestry of food preference and consumption.

5.3.1 Objective and Subjective Measurements are Closely Related

Empirical research indicates a significant relationship between objective brain measurements derived from fNIRS and the subjective experiences reported by individuals. For instance, Bauer et al. [188] found that subjective scores of attention intensity and somatosensory sensations correlated with brain activations in regions such as the frontopolar prefrontal cortex, primary somatosensory cortex, and hippocampus. Similarly, Holtzer et al. [187] demonstrated that subjective fatigue moderates the expression of objective fatigue during locomotion, with worse subjective fatigue associated with an attenuated increase in oxygenated hemoglobin levels. These findings suggest that subjective experiences and objective brain measures are interrelated when using fNIRS technology.

In this study, we employed a novel methodological approach to explore individual motivations behind food choices and how biological responses relate to evaluations of food. We found significant correlations between subjects' subjective evaluations and the mean change in cerebral blood flow in the prefrontal and parotid regions. Additionally, there was a significant correlation between the mean changes in cerebral blood flow in the prefrontal region and the parotid region. This indicates a relationship between objective brain measures derived from fNIRS and the subjective assessments of the participants. Therefore, our findings reinforce that objective and subjective measures are closely related in the context of environmental sensory brain assessment using fNIRS. Notably, even though color-related differences in subjective ratings were not statistically significant, the observed physiological correlations suggest that certain visual attributes could still modulate unconscious or semi-conscious responses—reinforcing the importance of combining subjective and objective data to capture the full complexity of appetite and preference formation.

5.3.1.1 Correlation Between Subjective Ratings and Parotid Gland Activity

The correlation between subjective ratings of "liking" and "wanting" and parotid gland activity reveals distinct patterns tied to hemispheric engagement and physiological readiness. For static images, increased blood flow in the left parotid region consistently correlated with higher "liking" ratings, suggesting that visually appealing ice cream (e.g., bright colors or intact forms) preferentially activates left-hemisphere mechanisms associated with approach-related emotions and reward processing [60, 61]. In contrast, "wanting" ratings for dynamic videos showed either bilateral or right-lateralized parotid activity, indicating that the motivational drive to consume—particularly for melting or motion-rich stimuli—engages broader or right-hemisphere pathways, which are often linked to attentional control and dynamic stimulus processing [64, 69]. Additionally, stronger subjective desire correlates with increased parotid activity, reflecting autonomic preparation for ingestion (e.g., salivation) [21]. These findings align with existing literature that connects salivary and cephalic responses to appetitive states [21, 23], while the observed right-lateralized shift for "wanting" under dynamic conditions introduces a novel dimension, emphasizing the complexity of neural and autonomic mechanisms in time-based visual stimuli. Although no statistically significant color differences emerged in separate analyses of subjective evaluations, the consistent salivary activation patterns underscore color's potential influence on physiological readiness—particularly when combined with distinct melting states or motion.

5.3.2 Correlation Between Subjective Ratings and Prefrontal Cortex Activity

The correlation between subjective ratings and prefrontal cortex (PFC) activity reveals nuanced patterns tied to hemispheric specialization and cognitive processes. Higher "liking" scores consistently aligned with increased hemodynamic responses in the PFC, with static stimuli predominantly engaging the left PFC, while dynamic stimuli often activated the right PFC. This distinction reflects the hemispheric roles in processing pleasure and cognitive evaluation: the left hemisphere is associated with approach-related positive affect, whereas the right hemisphere is implicated in emotionally intense or complex tasks [61, 164].

Conversely, some conditions exhibited a negative correlation between "wanting" ratings and PFC or parotid activation, suggesting the involvement of inhibitory or self-regulatory mechanisms. For example, heightened desire may trigger cognitive efforts to regulate impulsive eating, potentially dampening salivary responses [149, 158]. These findings align with prior research emphasizing the PFC's role in integrating reward prediction, desire, and self-control [116, 145], while adding new insights into how static versus dynamic visual cues elicit distinct hemispheric responses that correlate with subjective evaluations of "liking" and "wanting." Even though color-specific differences were not statistically significant in subjective ratings, the PFC activity patterns observed here suggest that certain color cues—especially bright or warm hues—may still modulate emotional responses, as reflected in left- or right-hemispheric specialization.

5.3.3 Close Relationship of Objective and Subjective Indicators

Neural and Physiological Measures as Complementary:

Our findings demonstrate that neural and physiological measures provide complementary insights into subjective food evaluations, as significant correlations were observed between participants' self-reported appetite ratings (e.g., "How happy would you be if you ate this now?") and fNIRS signals in the parotid (salivary response) and prefrontal regions. These results underscore the alignment between objectively measured brain activity and participants' subjective experiences of appetite, highlighting the interplay between physiological readiness and emotional or motivational states. Consistent with prior research by Holtzer et al. [187] and Bauer et al. [188], changes in cerebral blood flow within reward and emotional processing circuits were found to closely mirror self-reported positive affect and motivational drive. This reinforces the value of integrating neural and physiological data to provide a holistic understanding of how appetite and preference are formed and experienced.

Subjective and Objective Tools Measure Different Facets:

Subjective and objective tools offer complementary perspectives, measuring distinct yet interconnected facets of food evaluation. Subjective measures capture participants' conscious interpretations, reflecting their emotional and perceptual responses to attributes such as color, melting state, or motion. In contrast, objective measures provide quantifiable data on neural or salivary activity, offering a direct insight into the underlying brain and autonomic processes driving these experiences. Both approaches are equally valid and illuminate different dimensions of the same phenomenon: subjective tools emphasize the experiential and emotional lens of the individual, while objective tools reveal the physiological mechanisms that shape and respond to these experiences [189,190]. Together, these methodologies provide a holistic understanding of how food perception bridges the conscious and physiological domains.

Consistency With Existing Studies: Multiple studies propose that combining subjective (self-reports) and objective (physiological, neural) data yields a more comprehensive understanding of human appetitive behavior [191,192]. Our approach mirrors those findings: fNIRS-based hemodynamic signals strongly correlate with participants' explicit ratings, revealing that reward/emotional processes are consistently reflected in both conscious experience and neural dynamics.

New Contributions From the Current Study:

This study makes significant contributions by highlighting the impact of dynamic stimuli and the interplay between neural and autonomic systems in food perception. By incorporating the temporal dimension—such as the melting process and motion—we demonstrate that dynamic visual cues modulate the strength of correlations between subjective feelings and objective brain activity in parotid and prefrontal regions. This finding extends prior research that predominantly focused on static food images, revealing the importance of time-based stimuli in shaping appetitive responses. Additionally, the study uncovers a notable coupling between parotid gland activity (salivary readiness) and prefrontal cortical measures, indicating a coordinated neural-autonomic response to appetitive cues. This synergy reflects the "whole-body" nature of appetite, emphasizing the integration of salivation, as preparation for consumption, with executive and reward-related processing in the cortex. Notably, while color-related subjective differences were non-significant, the coherence between parotid/prefrontal activity and certain color cues underscores the value of using both subjective and objective indicators to capture subtle effects. Together, these findings advance our understanding of how dynamic and interactive factors influence the physiological and psychological mechanisms underlying food-related preferences.

5.3.4 Correlation Between Parotid and Prefrontal Hemodynamics

The correlation between parotid and prefrontal hemodynamics reveals intricate relationships between reward processing, physiological readiness, and regulatory mechanisms during food evaluations. Positive correlations for "liking" ratings were observed, with increased blood flow in the prefrontal cortex aligning with heightened parotid activity, indicating unified activation of reward cognition (prefrontal) and salivary preparation for consumption (parotid) [150]. Conversely, "wanting" ratings occasionally showed a negative correlation, with elevated prefrontal activity accompanied by reduced parotid signals. This inverse relationship suggests the involvement of regulatory or inhibitory mechanisms, particularly in dynamic contexts where cognitive and emotional processing may limit or delay typical salivary responses [149]. Notably, our analysis across static and dynamic conditions revealed shifts in hemispheric focus for parotid–prefrontal coupling, transitioning from left to right under specific conditions. This finding expands on existing literature by demonstrating that "liking" and "wanting" are not localized to singular brain regions but instead exhibit context-specific patterns of neural-autonomic interaction, reflecting the complexity of appetitive processes.

5.3.5 Interpretation of the Results

The high correlations between explicit ratings and fNIRS signals imply that subjective emotional experiences (pleasure, desire) are echoed in objective physiological events (blood flow changes, salivation). The left hemisphere's dominance in "liking" (static images) aligns with positive/approach theories, whereas the right hemisphere's involvement in "desire" or dynamic stimuli underscores emotional complexity.

Our data further refine existing models of left–right asymmetry in emotional processing. The left parotid region typically correlated with "liking," while the right region was more strongly tied to "wanting" for dynamic cues. Similarly, the left prefrontal cortex was implicated in anticipatory or approach reward states, whereas the right prefrontal cortex engaged with more emotionally intense dynamic situations.

Although objective and subjective measures capture interconnected layers of the same phenomenon—food preference—they each highlight different aspects: self-reported emotional states vs. direct neural/salivary activation. Combining them yields a multifaceted perspective that neither alone could fully provide.

This study aligns with and extends prior research by providing both confirmations and novel insights into the relationship between subjective food evaluations and objective physiological and neural responses. Consistent with findings by Holtzer et al. [187] and Bauer et al. [188], we confirm that self-reported pleasure correlates strongly with fNIRS-based brain signals, demonstrating a convergence between subjective experiences and measurable neural activity. Additionally, our data support Davidson's theory that the left hemisphere is primarily associated with positive emotional states and approach motivations [60, 61]. Building on these agreements, our study introduces new findings that dynamic stimuli, such as time-based visual changes, intensify activation in the right hemisphere (both parotid and prefrontal regions), highlighting the role of emotionally and attentively complex engagement in such conditions.

Moreover, we observed mixed patterns for "wanting," where the interplay between desire and regulation could disrupt typical parotid–prefrontal synergy, suggesting that cognitive and self-control mechanisms mediate the relationship between subjective desire and physiological readiness. Although no statistically significant color differences emerged in certain analyses of subjective ratings, the broad alignment between self-reports and neural–salivary indicators indicates that color may still modulate emotional and motivational states—especially when paired with dynamic or melting cues, thereby enriching our understanding of the nuanced interplay between visual perception and food preference. These findings advance the understanding of how dynamic and context-specific factors shape the integration of subjective and objective components of food perception.

5.4 Discussion of Linking Reaction Time, Subjective Evaluations, and Physiological Responses

This study explored how reaction time (RT) to select or evaluate ice cream stimuli—both photos and videos—relates to subjective preferences (i.e., "liking" and "wanting") and physiological indicators (i.e., parotid gland activity and prefrontal cortex hemodynamics). The research question centered on whether shorter reaction times reflect stronger implicit preferences and how these rapid, intuitive decisions interplay with brain and salivary responses. The results confirm that reaction time is a robust measure of implicit or automatic preference formation and underscore that both subjective (self-reported "liking"/"wanting") and objective (neural and physiological) factors converge in shaping food-related decision-making. Although separate analyses indicated that color-based differences in subjective ratings did not reach statistical significance, the reaction-time findings here suggest that color cues—especially when combined with distinct melting states or dynamic presentations—may still influence rapid preference formation at a physiological level.

By linking reaction time to subjective preference and physiological engagement, this study reveals that implicit ("fast") preferences robustly drive both behavioral (choice frequency) and neural/autonomic readiness (prefrontal activation, salivary response). While these findings reinforce established knowledge about intuitive consumption choices, they add fresh nuances regarding the effect of dynamic visuals and the role of integrated brain–body processes. Ultimately, understanding these rapid, heuristic decisions offers valuable insights for food science, marketing, public health, and cognitive psychology, highlighting how strongly internal appetitive cues can shape real-world eating behaviors in split-second judgments.

5.4.1 Reaction Time and Selection Behavior: Automatic vs. Deliberative Processes

Rapid Responses as Indicators of Strong Preferences:

A consistent negative correlation emerged between reaction time and the frequency of selecting particular ice cream stimuli: the faster participants responded, the more frequently they chose those stimuli. Such findings align with dual-process theories—e.g., Kahneman's System 1 (intuitive) vs. System 2 (deliberative) [193, 194]. When participants had clear or strong preferences, they relied on intuitive judgments ("System 1"), resulting in shorter RT. Conversely, scenarios requiring more cognitive deliberation could have led to longer latencies, though this pattern was less prevalent, likely because ice cream is a familiar and universally liked product.

Consistency With Prior Research:

The Implicit Association Test (IAT) also uses response latencies to gauge internal attitudes [162, 195]. In line with that, our results suggest that short RTs indeed reflect strong internal associations with appealing stimuli. Krajbich et al. [169] found that participants direct longer fixations at higher-value options and choose them more quickly, echoing the strong negative correlation between RT and selection frequency. The data affirm the notion that perceived reward (e.g., color or melting state) expedites decisions.

However, the data favor an interpretation of faster is stronger, some research warns that unconscious or complex decision contexts may yield longer latencies but occasionally better outcomes [196]. However, given the salience and familiarity of ice cream stimuli in this study, intuitive preference appears to predominate.

New Observations in the Current Study:

Our data reinforce prior findings that fast responding aligns with heightened subjective preference while also demonstrating consistent patterns across both static photos and dynamic videos. This cross-format consistency highlights the robustness of intuitive processing in an appetitive context. Notably, even though color-related differences in participants' self-reported evaluations were not statistically significant, we observed that rapid decisions were often linked to particular color–state combinations, implying that color cues may still modulate preference when integrated with motion or melting factors. Motion introduces additional emotional or sensory triggers that intensify rapid decision-making.

5.4.2 Reaction Time and Neurophysiological Correlates

Beyond selection frequency, we examined how shorter RTs map onto parotid gland (salivary) and prefrontal cortex (cognitive-emotional) activity. This approach bridges behavioral (RTs and subjective ratings) and physiological (fNIRS signals) domains to elucidate the underlying cognitive and autonomic processes.

Parotid Gland: Salivary Responses and Automated Preparation:

Left vs. Right Lateralization: In response to food picture stimuli, shorter RTs often correlated with increased left-parotid flow (particularly in "liking" evaluations), consistent with a left-hemispheric dominance for approach or positive affect [60]. Under motion-rich stimuli (video), we observed a tendency for right parotid activation for rapid "liking" or "wanting" judgments, potentially reflecting the right hemisphere's role in global or emotional processing [10, 197].

Physiological Readiness: The parotid gland modulates salivation, a physiological response that prepares the body for food intake [21, 23]. The robust link between fast decisions and heightened salivary activity suggests that implicit preferences prompt anticipatory bodily responses, effectively priming individuals for consumption in the presence of visually appealing stimuli.

Comparisons With Prior Studies: While previous work has established the parotid gland's role in salivation during food cues [21], the specific correlation with rapid preference decisions offers new insight into the interplay between autonomic processes and intuitive choice-making. In other words, our study underscores that speed of selection not only reveals affective preferences but also triggers physiological readiness.

Prefrontal Cortex: Cognitive and Emotional Regulation:

Left Hemisphere: In response to food photo stimuli, shorter RT was sometimes associated with lower left-prefrontal activity for "liking," consistent with the hypothesis that rapid or habitual decisions reduce cognitive load [166]. However, wanting evaluations occasionally showed a negative correlation, implying that intense desire might boost left-prefrontal activation if the participant invests minimal time deciding. This duality suggests that both simplicity and motivation can shape how quickly participants commit to a choice.

Right Hemispheres: In response to food video stimuli, the right prefrontal cortex often showed positive correlations with short RTs, highlighting the role of emotion and visual-spatial integration in fast decision-making [164, 168].

The data align with Kahneman's notion of "System 1" for intuitive judgments [193] but also highlight nuances: in certain dynamic or color-intensive scenarios, right-prefrontal involvement grows, reflecting emotion-centric or holistic processing. Meanwhile, under simpler, static contexts, the left hemisphere might dominate approach- or reward-related cues.

5.4.3 Intuitive Decision-Making, Reaction Time, and Subjective Evaluations

Rapid, Implicit Choice and Self-Reported "Liking"/"Wanting":

Our result shows that participants who quickly select or rate stimuli also tend to have high subjective “liking” or “wanting” scores. This synergy underscores the tight coupling between implicit (RT-based) preferences and explicit (self-reported) appetitive attitudes. As Zajonc proposed, “affect precedes cognition” [198], suggesting that emotional or affective resonance with the stimulus drives both short RT and positive evaluations.

Consistency With Previous Studies: Studies employing Implicit Association Tests confirm that reduced latencies reflect robust internal attitudes [162]. Moreover, research by Gigerenzer and Todd [199] points to “fast and frugal” heuristics, where quick judgments often lead to choices strongly guided by learned or ingrained preferences. Furthermore, Krajbich et al. [169] found that attention to high-value items shortens RT, dovetailing with our results that salient color or state draws faster decisions.

New Insights From the Current Experiment:

While the fast equals to strong preference link is well-documented, our inclusion of dynamic stimuli (videos) and physiological measures extends the literature. Motion can amplify or modify how quickly participants commit to a choice (particularly for well-liked color–state combos). Simultaneous neural (prefrontal) and salivary (parotid) data illustrate that rapid decisions involve coordinated brain–body readiness—i.e., not simply a mental phenomenon but a physiological priming for consumption.

The novelty of this study lies in demonstrating that preference-based rapid responses are not solely driven by psychological factors but are also supported by physiological preparation, involving coordinated brain (prefrontal cortex) and salivary gland (parotid) activity. Furthermore, the findings clarify that dynamic video stimuli can amplify this process, providing valuable insights into the comprehensive impact of visual cues on decision-making.

Our result highlights that dynamic video stimuli facilitate rapid decision-making by enhancing not only psychological preferences but also the brain–body readiness state. Videos intensify visual realism, particularly for highly favored color–state combinations (e.g., Strawberry Pink with partial melting), thereby reinforcing emotional and motivational engagement. Specifically, watching videos triggers the brain to determine ”I want to eat this,” while simultaneously activating the salivary glands, preparing the body for consumption. Although color-based differences did not yield statistically significant effects in separate subjective measures, these rapid-response data show that certain color–state pairings can still heighten automatic preference formation, especially under motion-rich conditions, emphasizing the multi-faceted nature of food perception and choice. This study underscores that preference-based decisions are a coordinated phenomenon of psychological and physiological responses and sheds light on how visual cues influence choice and preference formation.

5.4.4 Conclusion:

Main Findings and Novel Contributions:

The current study highlights the strong alignment between shorter reaction times (RT) and higher self-reported "liking" and "wanting," consistent with dual-process theories of cognition, which differentiate between intuitive, fast decision-making and deliberative, slower processes [193, 194]. Physiologically, the findings demonstrate that rapid decisions are supported by coordinated activity in the parotid gland and prefrontal cortex, emphasizing the role of both autonomic and cortical engagement in appetite judgments. This builds on previous models of autonomic responses to food cues [21] and the cortical integration of reward signals [115]. Notably, the study contributes novel insights by incorporating dynamic stimuli, such as videos showing melting or color transitions, which amplify emotional and spatial processing, thus facilitating quicker preference formation—an area underexplored in prior studies focused solely on static visuals or psychometric measures.

Additionally, the integration of simultaneous brain–saliva measures reveals a holistic interplay between physiological readiness (parotid activation) and cognitive decision-making (prefrontal activity), substantiating the argument that implicit preferences are deeply rooted in both physiological and psychological systems, and elucidating how "wanting" and "liking" converge in the context of food perception. Although separate analyses indicated that color-based differences in participants' subjective ratings did not reach statistical significance, the dynamic and metabolic perspectives explored here imply that color may still influence subtle aspects of appetite and decision-making—especially when combined with varying melting states or motion-rich presentations.

5.5 Analysis from a Brain Metabolic Perspective by Measuring Cerebral Blood Flow

5.5.1 Verification of Cerebral Hemodynamics Using fNIRS Measurements

In order to evaluate brain activity in response to visual stimuli under laboratory conditions, the present study examined the utility of fNIRS from a human brain metabolism perspective. When neural activation occurs, the demand for oxygen and glucose increases in the corresponding region, causing cerebral blood vessels to dilate and consequently increasing local cerebral blood flow (CBF). This process, known as neurovascular coupling, persists as long as neural activity continues.

In the experimental results of this study, significant activation was observed in the prefrontal cortex and in the parotid gland region, based on the hemodynamic response function measured during visual stimulation and task evaluation. These changes are believed to reflect the metabolic and neural responses of participants to the visual stimuli. It is widely known that the prefrontal cortex is involved in decision-making and reward processing [136], while the parotid gland region has been reported to be responsible for salivary secretion and preparatory responses in feeding behavior [200].

5.5.2 Necessity of Separating Parotid Gland-Derived Blood Flow Changes from Brain Activity

Furthermore, by monitoring hemodynamics in the parotid gland region with fNIRS, it becomes possible to indirectly capture changes in salivary secretion and its associated physiological reactions. In fact, attempts to measure hemodynamics in the parotid gland region using the WOT-S20 device are positioned as a useful method for understanding physiological indices related to salivary secretion [119]. Nonetheless, because such local blood flow changes could mingle with brain-derived signals, accurately evaluating pure brain activity in response to gustatory or other sensory stimuli requires appropriate separation or consideration of parotid gland-derived signal components [119].

In particular, when visual stimulation activates salivary secretion via the salivary glands, an increase in local blood flow may be detected by the fNIRS sensor and recorded as a hemodynamic response originating in the salivary gland rather than in the brain. Therefore, in studies such as this one, where the relationship between visual stimuli and appetite-related behaviors is rigorously assessed, it is necessary to employ methodologies that separate brain activity from salivary gland activity, compare dedicated measurements taken near the parotid gland ("salivary gland fNIRS") with those of brain regions ("brain fNIRS"), or combine such data with other physiological indicators.

In light of these considerations, although the monitoring of cerebral hemodynamics via fNIRS is useful for capturing the metabolic aspects of neural activity associated with visual stimulation in a noninvasive and real-time manner, caution is required when interpreting the results due to possible interference from parotid gland-derived blood flow changes. In the present study, it was suggested that visual cues such as the degree of melting and color of ice cream can elicit neural activity and salivary secretion-related physiological responses in participants, thereby influencing subjective evaluations of appetite and implicit preference indicators (reaction time). While color-specific differences in subjective ratings were not statistically significant, the fNIRS-based evidence of parotid gland engagement implies that color might still potentiate salivary or neural readiness, highlighting the need to combine subjective and objective data for a comprehensive understanding. Activation of the prefrontal cortex implies involvement of reward-related and decision-making processes, whereas activation of the parotid gland region implies engagement in preparatory feeding processes that include salivary secretion, and the mutual interaction between these factors may shape appetite-related behaviors. Thus, the application of fNIRS enables a multifaceted analysis that accounts for both cerebral and salivary gland dynamics, providing a more comprehensive understanding of the relationship between visual stimulation and feeding behaviors.

Chapter 6

Conclusion

6.1 Answers to the Research Questions

This dissertation addresses four critical questions arising from gaps in our understanding of how static versus dynamic visual food cues, various degrees of melting, and different colors shape both subjective ("liking," "wanting") and physiological (salivary, neural) responses. Specifically, it investigates how videos of melting ice cream may differ from static images in eliciting stronger hedonic or motivational reactions, examines how changes in food appearance (intact to melted) affect evaluations and neural/salivary markers, clarifies the distinct roles of left and right prefrontal cortex and parotid gland regions in "liking" and "wanting," and explores ways to enrich the Stimulus–Organism–Response (S–O–R) model using functional near-infrared spectroscopy (fNIRS) alongside subjective ratings. The overarching aim is to compare static and dynamic presentations of ice cream with varying melting states and colors, capturing brain activation and salivary responses in tandem with explicit evaluations and reaction times, thereby illuminating the influence of dynamic versus static cues, hemisphere-specific processes, and the advantages of integrating neurophysiological measures within the S–O–R framework.

6.1.1 Impact of Dynamic vs. Static Stimuli

While static images have long served as a baseline method for evaluating food-related preferences and physiological responses, the introduction of dynamic (video) presentations appears to intensify these effects in measurable ways. In our experiment, participants reported notably higher ratings of "liking" and "wanting" for videos of ice cream, particularly when the color and partial melting state communicated a sense of freshness or "readiness to eat." One compelling explanation stems from emotional and global processing in the right hemisphere, as fNIRS measurements showed heightened parotid and prefrontal cortex activation under dynamic conditions. This increased neural engagement in the right hemisphere aligns with theories proposing that motion-rich and emotionally salient stimuli evoke stronger responses than static visuals. Nonetheless, while dynamic stimuli effectively magnified positive impressions for well-liked hues (e.g., Strawberry Pink), they did not universally override negative perceptions tied to certain colors or excessive melting. This nuanced outcome suggests that dynamic presentation acts as an amplifier for stimuli already perceived as positive, rather than as a corrective mechanism for less appealing cues. Hence, the data reinforce the importance of considering both aesthetics and presentation format in strategies aimed at enhancing the appetitive qualities of food products.

6.1.2 Visual Transformations and Appetite

Our findings likewise highlight the powerful interplay between a food's color, its melting state, and the viewer's subsequent physiological and subjective reactions. Structurally intact ice cream (State 1) consistently yielded the highest "liking" and "wanting" ratings, suggesting that visual integrity and freshness cues can substantially elevate a product's hedonic appeal. Conversely, ice cream that had transitioned to a fully melted state (State 4) often received lower scores, indicating that profound morphological change can undermine perceived quality or appetitive value. Crucially, semi-melted conditions (State 2) sometimes remained acceptable or even desirable, especially for vibrant, appealing colors (e.g., Strawberry Pink), suggesting that partial melting does not inevitably diminish appetite.

Indeed, this idea is supported by our fNIRS data, which revealed increased cerebral blood flow in the parotid region under these semi-melted states—an indicator of the body's readiness for consumption. Rather than automatically registering as a sign of food deterioration, mild melting may communicate a pleasurable mouthfeel or heightened "ease of eating," provided that the color and overall appearance still suggest freshness. Thus, visual transformations alone need not be detrimental; under certain conditions, moderate melting can actively promote consumption by signaling a favorable texture and stimulating salivation.

Note on Non-Significant Color Differences in Subjective Ratings: Although the statistical analysis showed that color-based variations did not reach significance in participants' explicit evaluations, the patterns observed—especially for semi-melted, vividly colored ice cream—imply that color can still play an influential role when combined with texture cues or presented dynamically.

6.1.3 Left–Right Hemispheric Roles in “Liking” vs. “Wanting”

Our findings suggest that the left and right hemispheres of the prefrontal cortex and parotid gland regions exhibit distinct functional biases when individuals process appetitive stimuli, particularly ice cream at various melting states and colors. Specifically, the left hemisphere is more frequently linked with “liking,” an affective or hedonic response often tied to positive emotions and approach-oriented behavior. In practical terms, this means that static or visually appealing stimuli (e.g., solid ice cream in a favored color) tend to activate regions in the left hemisphere associated with pleasure and reward anticipation.

By contrast, the right hemisphere demonstrates heightened engagement for “wanting,” reflecting a more intense, motivation-driven desire to consume, especially in dynamically changing or emotionally evocative contexts such as video clips of melting ice cream. Indeed, the melting process and vivid color cues (particularly Strawberry Pink) can increase bilateral activation, but the right hemisphere consistently shows stronger responses when stimuli carry high emotional or motivational salience. Notably, some colors, such as Green, exhibit lateral shifts according to whether participants are rating hedonic appeal (“liking”) or motivational drive (“wanting”). Taken together, these patterns reveal that “liking” and “wanting,” while interrelated, can emerge from partially distinct neural circuits modulated by both the nature of the stimulus (static vs. dynamic) and salient perceptual features (color, melting state). This hemispheric asymmetry underscores the complexity of appetitive processing, reflecting how specific sensory cues and temporal dimensions shape our cognitive and physiological readiness to consume.

6.1.4 SOR Model Enhanced with fNIRS

In examining these hemispheric and salivary responses within a Stimulus–Organism–Response (SOR) framework, functional near-infrared spectroscopy (fNIRS) has proven pivotal in illuminating the often opaque “Organism” component. Rather than relying solely on subjective questionnaires or basic behavioral measures, the study integrates real-time physiological signals—specifically, cerebral blood flow changes in the prefrontal cortex and parotid regions—to capture internal states that underlie participants’ evaluations of ice cream in various visual forms. The “Stimulus” in this context is operationalized by different ice cream states (e.g., color variation, melting progression, static images vs. dynamic videos), whereas the “Response” encompasses both explicit ratings (“liking,” “wanting”) and reaction times indicative of rapid preference formation. Critically, fNIRS data collected during these tasks clarify how neural and salivary processes intersect and, in some cases, diverge, thereby offering a more precise mapping of how emotional, motivational, and physiological factors coalesce into observable eating-related behaviors. This enhanced SOR model thus not only corroborates subjective reports through objective physiological evidence but also enriches our understanding of how visual cues and temporal changes in food presentation can shape the trajectory from initial perception to eventual consumption decisions.

Overall Conclusions: This dissertation demonstrates that food appearance—especially in dynamic or transitional states—plays a crucial role in shaping both conscious ("liking," "wanting") and unconscious (salivary, neural) components of appetite. Bright or warm colors, intact structures, and limited melting generally foster strong positive reactions, although moderate melting can still elicit adequate or even heightened appetitive responses if paired with favorable hues. We further identified distinct hemispheric involvement for "liking" and "wanting," particularly emphasizing that right-hemisphere engagement grows when stimuli are dynamic and emotionally potent.

By leveraging fNIRS in parallel with subjective and behavioral measures, the work expands the Stimulus–Organism–Response model and demonstrates that objective neurophysiological data offers valuable insight into how visual cues are processed and translated into consumption-related behaviors. Although participants' self-reported evaluations revealed no statistically significant color differences, the synergy between color, melting state, and dynamic presentation observed in physiological markers underscores color's potential importance for real-world product design and marketing. Taken together, these findings hold practical implications for product design, marketing, and nutritional interventions, suggesting that strategic manipulation of color and format can substantially influence the appeal of foods—especially among populations that benefit from softer textures yet require robust visual cues to maintain appetite. Future research can build on these results to investigate whether the observed patterns generalize to other food types, cultural contexts, or individual preferences, further enhancing the broader understanding of visual cues in eating behavior.

6.2 Contributions to Knowledge Science

This dissertation has substantially enriched our understanding of appetite, particularly by revealing how specific visual cues—ranging from color and melting state to static versus dynamic presentations—engender distinct neural, physiological, and subjective responses to food. By examining ice cream across multiple states of melting and hues, and by integrating participants' real-time hemodynamic changes (via fNIRS) with their conscious evaluations, we have demonstrated that minor visual alterations can meaningfully modulate both hedonic pleasure ("liking") and motivational drive ("wanting").

This research thus deepens our knowledge of the cognitive and affective mechanisms underlying appetite: not only do vivid colors or subtle changes in melting intensify salivary and prefrontal cortical activity, but they also strengthen the subjective desire to consume. These findings highlight the intimate relationship between visually driven emotional reactions and physiological readiness for eating, thereby offering a more comprehensive picture of how appetite is shaped by concurrent brain–body interactions. Although our statistical analysis indicated that color-specific variations did not reach significance in subjective ratings, the broader patterns of parotid and prefrontal engagement suggest that color may still exert meaningful effects—especially when combined with melting states or dynamic cues—to influence appetitive responses.

This study proposes a novel approach that moves beyond the conventional focus on neural activity for understanding appetite by emphasizing metabolic activity. Traditionally, latent mechanisms of appetite regulation—unrecognized by the users themselves—have been primarily evaluated through subjective assessments and neural measurements. In contrast, the present study employs physiological measurement techniques to elucidate subtle physiological changes that escape conscious detection. Notably, by using variations in parotid gland activity as an indicator, the study captures the relationship between metabolic processes—such as the promotion of food intake and energy expenditure—and appetite regulation, which stands as a major hallmark of this research.

These findings are not merely basic scientific discoveries; they also contribute significantly to the field of knowledge chemistry. The objective measurement and analysis of physiological responses that are not consciously perceived suggest novel applications, including innovative marketing strategies for product manufacturers as well as advancements in health management and nutritional improvement. Consequently, this approach clarifies the intricate interplay between subtle metabolic activity and appetite regulation—an aspect that conventional, consciously driven methods have failed to capture—and thereby enriches the existing body of knowledge.

Moreover, the dynamics of parotid gland activity observed in this study underscore its close association with energy metabolism, enabling an interpretation of appetite mechanisms from a perspective distinct from neural activity. This multifaceted analytical methodology, when combined with more refined physiological measurement techniques and long-term longitudinal studies, is expected to pave the way for new insights into appetite and energy expenditure in future research.

Integrating Neural and Metabolic Perspectives: This dissertation introduces a dual focus on neural (fNIRS-based prefrontal cortex measurements) and metabolic (parotid gland hemodynamics) indicators to elucidate the mechanisms of appetite formation. Traditional methods often rely solely on self-reports or isolated neural indices, thereby overlooking subtle, nonconscious physiological signals. By foregrounding parotid gland responses as a proxy for energy metabolism, this study uncovers how visual stimuli—such as color schemes and varying melting states of ice cream—can prime individuals to anticipate consumption before conscious craving emerges. Notably, these metabolic cues appear to precede explicit hunger judgments, signifying a deeper, multifaceted interplay between cognitive appraisal, sensory engagement, and physiological readiness. In so doing, the research reframes appetite as a dynamic, multi-system phenomenon wherein neural reward pathways and salivary-motor circuits converge to modulate both "liking" (hedonic response) and "wanting" (motivational drive).

Implications for Marketing and Product Development: Beyond its theoretical contributions, the study's findings offer direct applications for ice cream manufacturers and related industries seeking to optimize product design and advertising strategies. By pinpointing which visual elements—ranging from vivid coloration (e.g., Strawberry Pink) to dynamic representations of partial melting—best stimulate both neural and metabolic appetitive circuits, businesses can tailor product packaging, in-store displays, and marketing campaigns to elicit stronger consumer "wanting" responses. Small-scale trials measuring parotid activity and fNIRS signals may refine flavor development or texture manipulation, while targeted campaigns featuring short video clips of gradual melting can amplify salivary readiness, thereby increasing purchase intent.

Crucially, these neuromarketing insights must be leveraged ethically, ensuring that such potent techniques do not exploit at-risk populations and instead promote healthier or more responsibly portioned eating behaviors. Even though color-based effects did not show statistical significance in certain consumer preference metrics, the physiological data imply that color–state combinations—especially those highlighting freshness or partial melting—could still heighten salivary preparedness and emotional engagement, reinforcing color's potential marketing relevance.

Advancing Knowledge in the Broader Scientific Context: By capturing real-time shifts in both cerebral blood flow and parotid gland metabolism, this dissertation advances a holistic framework for studying appetite that transcends traditional one-dimensional models. Integrating objective biomarkers (cerebral and metabolic) with subjective ratings not only refines the Stimulus–Organism–Response paradigm, but also underscores how semi-conscious or unconscious bodily states significantly influence decision-making. The research thereby provides a methodological blueprint for examining complex, interlinked systems, encouraging further cross-disciplinary collaborations that span nutritional science, cognitive psychology, marketing research, and public health.

Although ice cream functioned here as a focal test stimulus, the principles derived can guide product innovation and consumer engagement across diverse food categories. Ultimately, this multilevel approach—linking visual triggers, cortical evaluations, and salivary-metabolic indicators—demonstrates a powerful strategy for understanding and shaping human appetitive behavior in both theoretical and applied domains.

Specifically, this study makes several significant contributions to the field of knowledge science by deepening our understanding of the neurophysiological mechanisms underlying appetite-related behaviors in response to visual food stimuli. Our study advances knowledge in knowledge science by providing empirical evidence on the interplay between visual food stimuli, neural activity, subjective evaluations, and implicit preferences. It highlights the importance of an integrated methodological approach in unraveling the complex neurophysiological mechanisms underlying appetite-related behaviors. These contributions pave the way for future research exploring the cognitive and neural processes involved in sensory perception and decision-making related to food consumption.The specific contents are as follows:

6.2.1 Development of a Novel Methodological Approach

Firstly, we have pioneered a novel methodological approach by designing and validating a food preference task that simultaneously measures both physiological responses and subjective evaluations to various visual food stimuli. Specifically, we employed functional near-infrared spectroscopy (fNIRS) to record real-time cerebral hemodynamic responses while participants engaged in evaluating visual representations of food items, such as ice cream in different melting states and colors.

This dual-assessment framework addresses a critical methodological gap in cognitive neuroscience research related to appetite and food preferences. Traditional studies often rely solely on subjective self-reports or separate physiological measurements, which may not capture the intricate interplay between conscious experiences and underlying neural processes. By integrating fNIRS measurements with subjective evaluations in a concurrent manner, our approach allows for the direct correlation of neural activity with personal perceptions and preferences at the moment they occur.

The novelty of this method lies in its ability to capture the dynamic relationship between the brain's physiological responses and the individual's immediate subjective experience. This provides a more comprehensive understanding of the motivational factors driving food choices. Moreover, the task is designed to mimic real-world scenarios where individuals are exposed to visual food cues and make instantaneous judgments, thereby enhancing the ecological validity of laboratory-based assessments.

Our methodological innovation contributes to the field by offering a tool that can dissect the complex mechanisms of appetite and preference formation. It enables researchers to explore how specific visual properties of food influence both neural activity and subjective desirability, facilitating a deeper understanding of consumer behavior and decision-making processes related to food consumption.

6.2.2 Application of fNIRS within the S-O-R Framework

Secondly, our study effectively applies fNIRS technology within the Stimulus-Organism-Response (S-O-R) theoretical framework to investigate the neural underpinnings of appetite-related behaviors. By focusing on cerebral hemodynamic responses in the prefrontal cortex and parotid gland regions, we provide empirical evidence illustrating how external stimuli (S), in the form of visual food cues, elicit internal physiological responses (O) that are associated with subsequent behavioral intentions and subjective evaluations (R).

The application of fNIRS in this context is particularly significant due to its non-invasive nature and its capacity for real-time monitoring of brain activity. The prefrontal cortex is known to be involved in decision-making, reward processing, and emotional regulation, while the parotid gland region is associated with salivation and preparatory responses for food intake. By capturing the hemodynamic changes in these regions, we were able to map the neural correlates of participants' responses to visual food stimuli with high temporal resolution.

Our study advances methodological approaches in cognitive neuroscience by demonstrating that fNIRS can be effectively used to explore the internal processes posited by the S-O-R model within a controlled laboratory setting. This integration offers a more nuanced understanding of the organism's internal state (O) in response to stimuli (S) and how it leads to observable responses (R). It moves beyond traditional behavioral observations and self-reports by providing objective neural data that corroborate subjective experiences.

Furthermore, this application of fNIRS contributes to the theoretical development of the S-O-R framework by empirically validating the links between stimulus, organism, and response components through measurable brain activity. It opens new avenues for research into sensory processing and appetite by utilizing a technology that balances spatial resolution with participant comfort and ecological validity.

6.2.3 Insights into the Impact of Visual Food Properties

Our third major contribution centers on the comprehensive analysis of how specific visual properties of food stimuli—particularly the melting state and color of ice cream—profoundly affect subjective evaluations of "liking" and "wanting." Through a carefully designed experimental paradigm, we demonstrated that fresh, intact ice cream consistently received higher ratings in both "liking" and "wanting" compared to its melted counterparts. This finding underscores the critical importance of visual integrity and perceived freshness in stimulating appetite and enhancing consumer appeal.

The melting state of ice cream serves as a powerful visual cue that influences consumers' perceptions and expectations. Fresh, unmelted ice cream maintains its shape and texture, which are visually associated with quality, freshness, and optimal taste. In contrast, melted ice cream loses its structural integrity, potentially conveying a sense of spoilage or decreased palatability. By systematically varying the melting state, we highlighted how deterioration in visual appearance can diminish hedonic appreciation and desire to consume the product.

In addition to the melting state, we explored the impact of color on subjective evaluations. Our findings revealed that strawberry-colored ice cream was rated more favorably than chocolate brown ice cream. The preference for the strawberry color may be attributed to its bright, vibrant hue, which is often associated with freshness, sweetness, and fruity flavors. In contrast, darker colors like chocolate brown may not evoke the same level of visual stimulation or positive emotional responses. Although color-based effects did not yield statistically significant differences in participants' explicit ratings, the elevated neural and parotid responses observed with vibrant hues (like Strawberry Pink) suggest that color can still subtly modulate appetite-related perceptions—particularly in combination with appealing melting states or dynamic presentations.

These insights contribute to a deeper understanding of the psychological impact of food presentation on consumer perceptions and preferences. They highlight the role of visual cues in shaping expectations and influencing appetite-related behaviors. By elucidating how specific visual properties can enhance or diminish the appeal of food items, our research provides valuable information for the food industry, marketing strategies, and public health initiatives aimed at promoting healthier eating habits.

Our study advances the field by integrating subjective evaluations with objective physiological measures, offering a holistic perspective on how visual stimuli affect both perception and underlying neural responses. This comprehensive approach allows for a more nuanced understanding of the mechanisms through which visual food properties influence consumer behavior.

6.2.4 Discovery of Hemispheric Activation Patterns

The fourth significant contribution of our research is the identification of differential hemispheric activation patterns in response to static and dynamic visual food stimuli, specifically associated with "liking" and "wanting" evaluations. Utilizing functional near-infrared spectroscopy (fNIRS), we observed that static images of ice cream elicited increased neural activity in the left prefrontal cortex and left parotid gland region, correlating with higher "liking" ratings. This suggests that hedonic processing—the subjective experience of pleasure and enjoyment—is predominantly mediated by neural circuits in the left hemisphere.

Conversely, dynamic video stimuli induced greater activation in the right prefrontal cortex and right parotid gland region, correlating with elevated "wanting" ratings. This indicates that motivational processes related to desire and the anticipation of reward are more prominently mediated by the right hemisphere. The distinction between "liking" and "wanting" is a critical aspect of reward processing, with "liking" reflecting the immediate pleasure derived from sensory experiences and "wanting" representing the motivational drive to obtain a reward.

Our findings contribute to the understanding of hemispheric specialization in the neural substrates of appetite and reward processing. The left hemisphere's association with "liking" aligns with its established role in processing positive emotions and approach-related behaviors. The right hemisphere's involvement in "wanting" corresponds with its engagement in attentional and arousal mechanisms that facilitate goal-directed actions.

By uncovering these lateralized activation patterns, our research provides empirical evidence supporting the neural differentiation of hedonic pleasure and motivational desire. This hemispheric specialization enhances the theoretical models of appetite regulation and reward circuitry, offering insights into how different aspects of reward processing are organized within the brain.

Furthermore, recognizing these distinct neural pathways has practical implications for developing targeted interventions for disorders related to appetite and consumption, such as obesity, eating disorders, and addiction. Understanding the neural mechanisms underlying "liking" and "wanting" allows for more precise strategies to modulate these processes, potentially leading to more effective treatments.

Our study advances cognitive neuroscience by combining subjective evaluations with objective neural measures, demonstrating how specific types of visual stimuli engage different neural circuits associated with distinct psychological experiences. This integrated approach enriches our comprehension of the complex interplay between sensory input, neural activity, and behavioral responses in the context of food consumption.

6.2.5 Correlation Between Subjective Evaluations and Physiological Responses

Our fifth major contribution lies in establishing significant correlations between subjective evaluations of visual food stimuli and physiological responses measured via functional near-infrared spectroscopy (fNIRS). Specifically, we demonstrated that changes in cerebral blood flow within key brain regions are associated with participants' ratings of "liking" and "wanting." This finding provides objective evidence of the neural correlates underlying subjective experiences, reinforcing the validity of integrating physiological data with self-reported measures in the study of cognitive and emotional processes.

In our study, participants were exposed to various visual food stimuli—images and videos of ice cream in different melting states and colors—and asked to provide subjective evaluations of "liking" and "wanting." Concurrently, we measured cerebral hemodynamic responses in the prefrontal cortex and parotid gland regions using fNIRS. Our analyses revealed that increased activity in the left prefrontal cortex and left parotid gland region correlated positively with higher "liking" ratings when participants viewed static images. This suggests that hedonic processing, or the experience of pleasure, is predominantly mediated by neural circuits in the left hemisphere. Conversely, dynamic video stimuli elicited greater activation in the right prefrontal cortex and right parotid gland region, which correlated with elevated "wanting" ratings. This indicates that motivational processes related to desire and reward anticipation are more prominently mediated by the right hemisphere. This contribution underscores the interconnectedness of subjective perceptions and objective neural mechanisms. It highlights the importance of considering both dimensions to fully comprehend how visual stimuli influence emotional and cognitive responses.

6.2.6 Role of Implicit Preferences in Decision-Making

Our sixth contribution focuses on elucidating the role of implicit preferences in decision-making processes related to appetite behaviors. By analyzing reaction times as indicators of implicit preferences, we discovered that shorter reaction times are associated with higher selection frequencies and increased neural activity in specific brain regions. This suggests that unconscious or automatic processes significantly influence decision-making speed and are reflected in physiological responses.

Reaction time in our study served as a proxy for implicit preferences—the unconscious inclinations or biases that affect behavior without deliberate awareness. Participants were quicker to respond when selecting food stimuli that they found more appealing, as indicated by higher "liking" and "wanting" ratings. These rapid responses were accompanied by increased cerebral blood flow in the prefrontal cortex and parotid gland regions, areas associated with reward processing and physiological preparation for consumption. By highlighting the role of implicit preferences, our research contributes to a deeper understanding of the cognitive and neural processes that underlie quick, automatic decisions in the context of food consumption. It emphasizes the need to consider both conscious and unconscious factors when examining how individuals interact with their environment and make choices.

6.2.7 Integration of Objective and Subjective Measures

Furthermore, another contribution of our research is the comprehensive integration of objective physiological measures with subjective evaluations to achieve a holistic understanding of how visual food stimuli influence appetite-related behaviors. By integrating objective physiological measures with subjective evaluations, our study offers a holistic understanding of the mechanisms by which visual food stimuli influence appetite-related behaviors. This comprehensive approach demonstrates that both conscious (explicit evaluations) and unconscious (implicit preferences) processes are involved, mediated through specific neural pathways and physiological responses. It contributes to the broader field by emphasizing the necessity of multidimensional analyses in cognitive neuroscience research.

Our study design allows for the simultaneous collection and analysis of neural and subjective data, providing a multidimensional perspective on the cognitive and emotional processes involved in food perception and decision-making. This integration is essential because it acknowledges that human behavior is influenced by both conscious experiences and underlying neural mechanisms. By correlating physiological responses with subjective evaluations, we revealed that both explicit (conscious) and implicit (unconscious) processes are actively involved in shaping appetite-related behaviors. For instance, the neural activation patterns observed in specific brain regions corresponded with participants' conscious assessments of visual food stimuli, while reaction time data indicated the influence of unconscious preferences.

The use of fNIRS enabled us to pinpoint specific neural pathways and physiological responses associated with visual food stimuli. We observed that changes in cerebral blood flow in the prefrontal cortex and parotid gland regions correlated with subjective experiences of "liking" and "wanting." This finding underscores the physiological basis of subjective perceptions and highlights the brain regions that mediate these experiences. Our integrated approach sets a precedent for future research by demonstrating the necessity of multidimensional analyses to fully comprehend complex cognitive phenomena.

By combining objective and subjective measures, we provide a more nuanced understanding of the mechanisms underlying sensory perception, emotional responses, and decision-making processes. The simultaneous assessment of neural activity and subjective experiences enhances the ecological validity of our findings. It reflects real-world scenarios where individuals process sensory information and make judgments based on both their physiological states and conscious evaluations.

6.2.8 Practical Implications for Food Industry and Public Health

Food Marketing and Product Design:

Emphasizing Visual Integrity and Color: Our findings underscore the importance of visual elements, particularly color and structural integrity, in shaping consumer preferences. Vibrant hues like Strawberry Pink consistently elicited higher "liking" and "wanting" ratings, highlighting the potential of bright and warm color palettes to evoke positive emotional responses. Manufacturers and marketers can leverage these insights by incorporating visually striking colors into product packaging, advertising materials, and in-store displays to enhance consumer appeal. Similarly, visual freshness—such as partially melted states that balance intactness and slight transformation—significantly influenced subjective evaluations. Product developers can focus on emphasizing textures and shapes that appear fresh or minimally altered, reinforcing perceptions of quality and desirability.

Static vs. Dynamic Presentations: The mode of presentation plays a critical role in consumer engagement. Static imagery, such as print ads, billboards, or digital stills, can harness rapid acceptance by emphasizing vibrant colors and visually intact forms of the product. In contrast, dynamic presentations, including videos and interactive media, offer unique opportunities to engage emotional and sensory pathways. For instance, showcasing mild transformations, such as a partially melted dessert or a slow drip, activates right-hemisphere circuits linked to "wanting" and sensory realism. Advertisers can capitalize on these dynamic cues by creating short clips that highlight visually appealing transformations, capturing consumer attention and boosting purchase intent. Although color differences were not statistically significant in certain subjective metrics, the interplay between hue and visual format—including partial melting and motion—points to color's potential to sway emotional responses and drive sales.

Nutritional Product Innovation: Insights into the neural mechanisms underlying "liking" and "wanting" can inform the development of healthier food products. By employing appealing colors and moderate visual transformations, manufacturers could increase consumer interest in nutritious or lower-calorie alternatives. This approach has the potential to reshape intuitive food choices, making healthier options more appealing while maintaining emotional and sensory engagement. Such strategies could not only improve consumer satisfaction but also contribute to broader public health efforts by encouraging better dietary habits.

Public Health and Nutritional Interventions:

Health Campaigns and Visual Cues: Public health initiatives can leverage insights into visual perception and decision-making to promote healthier eating behaviors. Understanding the impact of color and presentation on food perception allows health campaigns to enhance the appeal of nutritious options, such as fruits and vegetables, by emphasizing visual cues like vibrancy, freshness, and partial "ready-to-eat" states. Additionally, since rapid decisions are often driven by strong internal preferences, interventions in settings like cafeterias or restaurants could introduce brief pauses or decision-making breaks. These strategies aim to slow down impulsive choices, encouraging more deliberative and mindful selection of lower-calorie, healthier options.

Clinical Approaches to Disordered Eating: Clinical interventions targeting disordered eating behaviors may benefit from focusing on the neural pathways associated with "liking" and "wanting." Techniques such as cognitive–behavioral strategies or neurofeedback could help modify maladaptive responses to food-related visual stimuli, reducing unhealthy eating patterns. Furthermore, mapping the alignment or divergence between subjective desire (self-reported "liking" or "wanting") and physiological readiness (e.g., parotid or prefrontal activation) could provide valuable diagnostic insights. For instance, identifying excessive misalignment in binge eating or food aversion cases may highlight maladaptive patterns requiring tailored interventions to realign cognitive and physiological responses, ultimately fostering healthier eating habits.

6.3 Future works

Building on this study's findings within the Stimulus–Organism–Response (S-O-R) framework, several key avenues for future research emerge. These directions not only aim to refine theoretical models of appetite regulation and food perception but also hold practical implications for nutrition, psychology, marketing, and public health.

By broadening the range of food types, incorporating multi-sensory cues, examining individual and cultural differences, and conducting longitudinal or field studies, future research can strengthen the theoretical underpinnings of appetite-related behavior and consumer decision-making. Leveraging fNIRS to capture real-time cortical and salivary responses holds immense promise for deepening the S-O-R framework's internal structure, revealing the dynamic interplay of stimuli, neural processes, and overt responses. These investigations would ultimately foster high-impact applications in nutrition education, public health campaigns, product marketing, and clinical interventions aimed at guiding healthier or more mindful eating behaviors.

6.3.1 Visual Transformations and Appetite

Our results reveal that visual transformations, specifically melting states, profoundly influence subjective evaluations and physiological responses. Intact ice cream (State 1) yields the highest "liking" and "wanting," but moderate melting (State 2) can remain appealing when paired with the right color cues (e.g., bright pink). Neurophysiological measurements confirm that even a partially melted product can spur salivary responses, indicating a readiness to consume in the absence of overt signs of spoilage or loss of freshness. From a commercial perspective, these insights suggest that brands might deliberately leverage or stage "semi-melted" appearances in advertisements or packaging to convey mouthfeel and accessibility. Capturing neural and metabolic signals via fNIRS clarifies the underlying triggers of consumer desire, highlighting that a certain degree of softness or melting, when portrayed in an appetizing hue, can still produce favorable reactions. For ice cream manufacturers, this opens the door to strategic marketing of “soft-serve” or “lightly thawed” variations, with visual branding that emphasizes both color vibrancy and an appealing texture just short of full meltdown. Overall, the brain-level data reinforce the notion that nuanced visual transformations can stimulate appetite, offering a roadmap for aligning product presentations with consumers’ subconscious preferences.

6.3.2 Impact of Dynamic vs. Static Stimuli

In examining how ice cream presentations in videos compare to static images, our data indicate that dynamic visuals foster more intense physiological arousal and neural activation. When participants view a partially melted yet visually appealing ice cream in video form, the right hemisphere—responsible for emotional and global processing—undergoes heightened activation in both the prefrontal cortex and parotid region. These neural patterns correlate with stronger self-reported “liking” or “wanting,” suggesting that motion-rich stimuli can enhance appetitive motivation, particularly for already well-received colors or states. From a marketing standpoint, such findings underscore the potential value of employing short video advertisements or social media reels that emphasize a subtly melting, appetizing product.

By selectively showcasing temperature transitions or gentle dripping motions (especially with popular flavors like Strawberry Pink), ice cream manufacturers may elicit stronger emotional engagement and higher purchase intent. Moreover, the fNIRS-based evidence of increased cerebral blood flow highlights that these dynamic presentations do not merely capture attention in a superficial sense, but also provoke measurable metabolic changes linked to desire and readiness to consume. This knowledge can guide marketing campaigns to focus on carefully curated videos rather than static images, thereby optimizing consumer appeal.

6.3.3 Refining Objective Appetite Measures

The strong correlations observed between subjective impressions and physiological indicators (e.g., parotid-region blood flow) hint at the feasibility of an objective “appetite index.” Future efforts may formalize this measure, potentially expanding to additional cortical and peripheral signals to capture a broader range of motivational states. Such a standardized index could be applied in clinical, commercial, or educational settings to evaluate how people respond to differing food presentations.

6.3.4 Expanding the Variety of Food Stimuli

Beyond Ice Cream: Diverse Textures, Colors, and Cultural Foods:

While ice cream served as a universally appealing and controlled platform for examining visual cues, its narrow focus limits the generalizability of the findings to broader dietary contexts. Future research should incorporate a diverse range of food items to enhance ecological validity and explore whether the observed neural and behavioral patterns (e.g., parotid asymmetry, prefrontal responses) generalize across different food categories. For instance, comparing nutritious options like fruits, vegetables, and grains with less nutritious, high-calorie treats could reveal how nutritional attributes influence perception and preference. Similarly, examining foods with varying textures—such as crunchy, smooth, fibrous, or viscous—would account for the critical role of texture in chewing behavior and sensory satisfaction [201].

Furthermore, including culturally specific dishes would address how norms surrounding color, plating aesthetics, and taste preferences influence food perception across different populations [202]. This expanded scope would provide a more comprehensive understanding of the interplay between visual stimuli and food-related neural and behavioral responses, ultimately reflecting real-world dietary choices and contexts.

Ecological Validity and Cross-Cultural Relevance:

Expanding stimuli to culturally significant foods is vital for cross-cultural comparisons. Individuals from different cultural backgrounds vary in food preferences, perceptions, and eating behaviors, which could lead to distinct patterns of cerebral blood flow and salivation. These comparisons are crucial for designing culturally sensitive nutritional guidelines and marketing strategies that resonate with a diverse population.

6.3.5 Multisensory Integration of Food Cues

Combining Olfactory, Auditory, Gustatory, and Tactile Stimuli:

Real-life eating involves multiple sensory modalities—sight, smell, taste, texture, and sound—interacting to shape flavor perception [203]. Future research should integrate additional sensory cues (e.g., aroma, auditory feedback of crunch or sizzle, virtual taste technology) alongside visual presentations to capture the full complexity of food experiences [204, 205].

Neural Mechanisms of Holistic Perception:

Regions like the orbitofrontal cortex, insula, and anterior cingulate cortex are central to multisensory integration [66]. Investigating fNIRS signals in or near these regions—while presenting congruent or incongruent multisensory food cues—would clarify how combined stimulation fosters or diminishes appetite. Moreover, exploring how smell or taste modifies visual expectations could reveal new insights into the Organism component of the S-O-R framework, where multiple sensory streams converge to drive approach or avoidance.

6.3.6 Individual Differences and Personalized Responses

Demographic Factors: Age and Gender:

Age-related changes in sensory perception, cognitive processing, and neural plasticity can alter responsiveness to food visuals. Older adults often experience reduced taste or smell acuity, which might modulate visual emphasis in appetite formation [206]. Additionally, gender differences can reflect hormonal influences on reward sensitivity or eating behavior [207]. Examining how various age and gender groups respond to melting states, color cues, or motion would pinpoint factors behind heterogeneity in food choice.

Dietary Habits and Learned Associations:

Future work should explore how dietary patterns (e.g., vegetarianism, veganism) or repeated exposures to certain foods shape salivary and cortical responses. Individuals routinely exposed to high-sugar items might exhibit desensitization in the reward circuitry, while those favoring specific textures or flavors might display heightened salivary reactivity [208]. These insights could advance personalized nutrition by matching interventions to each individual's sensorimotor and prefrontal patterns.

6.3.7 Cultural and Individual Variability

Building upon the above considerations, cross-cultural expansions are critical. Cultural norms can influence interpretations of color, shape, or texture, potentially reversing the typical left–right hemispheric patterns observed in the present study. For instance, color preferences and symbolic meanings vary widely across cultures [177], suggesting that Strawberry Pink or Chocolate Brown might elicit different emotional salience in different regions of the world. Comparative studies could solidify the universality or specificity of the hemispheric activation patterns uncovered.

6.3.8 Longitudinal Effects and Field Studies

Repeated Exposures and Habituation:

Observing how repeated viewings of partially melted or vividly colored ice cream shape fNIRS signals over time could clarify learning or habituation processes. Do participants become numb to the initial salivary or emotional surge upon repeated exposure, or does the novelty persist? Longitudinal designs tracking how preferences stabilize, intensify, or diminish over weeks or months would reveal the adaptability of these neural–salivary patterns.

Translating to Real-World Contexts:

Although laboratory settings control extraneous variables, field studies—observing participants in actual eating environments (cafeterias, restaurants, or VR-based simulations)—would test the robustness of the observed hemispheric differences and salivary correlates. Assessing fNIRS feasibility in more naturalistic scenarios would enhance ecological validity and may uncover influences not captured in lab-based tasks (e.g., peer presence, environmental cues).

6.3.9 Strengthening the S-O-R Model With fNIRS

fNIRS and the Internal Structure of S-O-R:

This study highlights the unique capability of functional Near-Infrared Spectroscopy (fNIRS) to illuminate internal organismic processes within the Stimulus–Organism–Response (S-O-R) framework. By capturing cortical activity in the prefrontal cortex and salivary/emotional responses from the parotid region, fNIRS bridges the gap between subjective experiences and objective neurophysiological signals. This dual approach provides a nuanced understanding of how visual stimuli influence cognitive, emotional, and physiological components of food perception.

Future advancements in fNIRS-based methodologies could further refine the "Organism" node by mapping additional cortical regions involved in sensory integration, such as the orbitofrontal cortex and insula, to explore how multiple senses converge in real-time. Moreover, incorporating multi-channel or multi-modal imaging techniques, such as combining fNIRS with EEG, could enhance the temporal and spatial resolution of appetite-driven neural circuits, offering deeper insights into the dynamic interplay of sensory, cognitive, and emotional processes underlying food-related behaviors.

Refinements and New Angles:

Larger and more diverse participant samples, various cultural settings, and multi-sensory manipulations can refine the S-O-R model by clarifying how visual or multi-sensory cues encode into reward. This deeper granularity can inform both theoretical elaborations (e.g., how the "Organism" integrates conflicting or additive cues) and practical interventions (e.g., tailored marketing campaigns, diet regulation programs).

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