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Neuronal correlates of basic taste perception and hedonic evaluation using functional Near-Infrared Spectroscopy (fNIRS)

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ABSTRACT

Sensory evaluation combined with neuromarketing is expected to improve the understanding of consumer behavior during food tasting. In this study, we used functional near-infrared spectroscopy (fNIRS) to monitor neuronal activation in the prefrontal cortex in response to basic tastes (sweet and bitter) and hedonically different chocolates (whole-milk chocolate and dark chocolate) in 34 healthy consumers. Sweet and bitter tastes tend to elicit decreased and increased neuronal activity, respectively. However, no significant differences in neuronal activation related to different sensitivities to basic tastes were observed. Regarding hedonic neuronal reactions, we detected a significant difference in brain activity between Likers and Dislikers for both chocolates, but the results were inconsistent between the two chocolates. Due to the small sample size, generalizing our results is critical, but these findings suggest that fNIRS could potentially be applied to predict consumer preferences for food, necessitating further research with larger sample sizes.

1. Introduction

In the food sector, sensory analysis techniques can be applied at various phases of the design process to evaluate a product's quality, consumer expectations, and reactions (Świąder & Marczewska, 2021).

The sensory evaluation of a product includes both the analytical sensory evaluation performed by a panel of experts and the affective test conducted on consumers. It is possible to learn more about a product being analyzed, its quality, and the factors influencing consumers' acceptance of it through sensory evaluation, which makes it easier to improve the product's quality or its reformulation (Świąder & Marczewska, 2021). Marketing decision makers in food companies can take advantage of sensory evaluations made by both consumers and panelists (Iannario et al., 2012).

However, working with a human as 'measuring instrument' in sensory evaluation is challenging due to great variability. From a statistical perspective, sensory evaluation is a scientific method in which experimental results are collected from a set of sampled consumers who express preferences and reactions to various aspects of the food and drink characteristics. In fact, the expressed choice is the outcome of a human decision, and it is reasonable to assume that this process is the result of intricate interactions influenced by past experiences, environmental factors, subjective covariates, and the characteristics of the objects, which also interact with the survey modality (Iannario et al., 2012). Approximately 95 % of all food choice processes occur unconsciously and are influenced by factors beyond the sensory properties of food (e.g., taste, smell) (Laves et al., 2022).

Since decision-making and sensory evaluation of food both occur in the brain, monitoring brain activity is expected to provide a potential tool for a more objective judgment of the sensory properties of food (Minematsu et al., 2018). Thus, neuromarketing is a promising approach. The primary focus of neuromarketing research is on the biological and neurophysiological mechanisms that underlie decisions and behavior. Compared to information from traditional market research studies, neuromarketing data can offer a more accurate representation of the underlying preferences. Through combination with sensory evaluation, an understanding of consumer behavior and individual preferences for food characteristics may be improved.

Although neuroimaging methods remain cost-intensive compared to traditional methods, market researchers see significant potential in neuromarketing for two main reasons. First, neuroimaging can offer a more efficient trade-off between utility and costs. This is based on the premise that consumers often cannot fully articulate their preferences, but their neuronal activity or physiological signals may reveal hidden

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data about their true preferences (Telpaz, Webb & Levy, 2015). Such data can be used to influence buying behavior, suggesting that the high cost of neuromarketing could be offset by improved product design and increased revenues. Studies have shown that neuromarketing can identify consumer preferences and predict purchases (Meyerding & Mehlhose, 2020).

Second, neuromarketing offers a precise approach that can be applied early in product design, especially for brands and labels. Neuromarketing information is believed to provide more accurate insights into underlying preferences and remain unbiased compared to traditional methods (Ariely & Berns, 2010). This allows for rapid evaluation of product concepts, eliminating unsatisfactory ones early and efficiently allocating resources to promising ideas. Research has demonstrated that neural activities can identify preferred brands, brand choices, and value experiences (Meyerding & Mehlhose, 2020; Chen, Nelson & Hsu, 2015; Plassmann et al., 208; Fehse et al., 2017).

One reason not using neuroimaging techniques in market research practice is the reliance of most researchers on functional magnetic resonance imaging (fMRI), which, despite its high spatial resolution, poses significant drawbacks for real-world behavior research. The immobility and artificial environment required for fMRI may not accurately reflect natural consumer behavior (Spence, 2019). In contrast, functional near-infrared spectroscopy (fNIRS) offers promising advantages. This non-invasive method maps brain blood oxygenation during neural activity and is less costly and more mobile than fMRI, allowing for use in natural settings (Jackson & Kennedy, 2013; Ferrari & Quaresima, 2012; Kopton & Kenning, 2014). fNIRS is comfortable, tolerant to body movement, and highly portable, making it a significant innovation in neuroeconomic research (Meyerding & Mehlhose, 2020; Pinti et al., 2018).

Despite its novelty, fNIRS has proven reliable and valid in various studies, both in and out of the lab. It has been used in realistic settings like walking in a city, driving, flying simulators, playing sports, and grocery shopping (Pinti et al., 2020; Yoshino et al., 2013; Verdière et al., 2018; Balardin et al., 2017). Additionally, fNIRS has been employed to study the neural correlates of consumer preferences and decision-making processes. Meyerding and Mehlhose (2020) demonstrated that fNIRS could effectively measure brain activity related to brand and package evaluation in a food-related context, suggesting that neuromarketing can complement traditional marketing research methods. They highlighted the portability and affordability of fNIRS, making it accessible for diverse marketing studies. In another study, Shahnavazi et al. (2021) investigated the impact of different lighting conditions on customer reactions to unpackaged fresh food. They used neuromarketing techniques, including fNIRS, to assess how lighting influenced consumer preferences, revealing significant effects on purchasing behavior. The application of fNIRS extends to sensory research, where it helps visualize sensory differences in taste perception. Laves, Mehlhose and Risius (2023) explored the use of fNIRS to understand how consumers perceive taste differences, combining consumer studies, sensory science, and neuroscience. Their findings indicated that fNIRS could identify neural responses to different taste stimuli, offering a novel approach to sensory evaluation. Krampe (2022) provided a comprehensive guideline for using mobile fNIRS in food marketing research. The study reviewed recent literature and highlighted methodological considerations for implementing fNIRS in various marketing contexts, emphasizing its potential to enhance the understanding of consumer behavior related to food products. Alvino et al. (2020) reviewed the use of various neuroscience tools, including fNIRS, in consumer neuroscience research. They found that fNIRS was particularly effective in studying brain activity associated with consumer decisions and sensory experiences. This study underscored the versatility of fNIRS in capturing real-time neural responses in naturalistic settings. According to ethical considerations, Spence (2020) discussed the ethical implications of using neuromarketing and sensory marketing techniques, including fNIRS. The study emphasized the need for ethical guidelines to ensure that such technologies are used responsibly, particularly concerning consumer privacy and informed consent.

Therefore, the present study aimed to combine sensory evaluation by consumers and neuroimaging to improve the objective comprehension of people's behavior during sensory tasting.

Several studies have been published on the location and use/dimension of brain activity in response to basic tastes and different foods or drinks with positive and negative hedonics. Qualitative and quantitative aspects of taste are generally accepted to be processed in the operculum and insula, which represent the primary cortical gustatory area (Minematsu et al., 2018). Experimental investigations in macaques have also shown that there is a primary taste cortical region in the anterior insula and adjoining frontal operculum, with a taste area in the orbitofrontal cortex (OFC), which is defined as the secondary taste cortex (O'Doherty et al., 2001).

It is generally accepted that the prefrontal cortex (PFC) is particularly related to emotional evaluations and values and plays a role in the control of decision-making and memory processing (Meyerding & Mehlhose, 2020). The lateral prefrontal cortex (LPFC) is a crucial area for the cognitive processing of taste and other food-related behaviors. The dorsolateral prefrontal cortex (DLPFC) is involved in memory formation associated with taste, and the ventrolateral prefrontal cortex (VLPFC) is activated by taste perception (Minematsu et al., 2018). The orbitofrontal cortex (OFC) is also involved in processing tastes that have both positive and negative affective valence, and different areas of the orbitofrontal cortex (OFC) may be activated by pleasant and unpleasant tastes (O'Doherty et al., 2001).

However, there has been less evidence for a general activation pattern related to flavor preferences, which may be useful for using neuronal data to predict consumer preferences for food and develop a more objective tool than conventional sensory techniques. Furthermore, only a few studies have investigated the relationship between innate preferences for basic tastes and learned flavor preferences for food products. A deeper study of this mechanism may help to better understand consumers' food-related behaviors. Moreover, it opens up more opportunities to influence consumers' decision-making processes related to food and nutrition through the application of consumer neuroscience (CN) and, therefore, has the potential to influence obesity, health, environmental, and climate crises. Sweet and bitter tastes were selected for this study due to their strong hedonic valence and significant impact on consumer preferences. Sweetness is typically associated with positive emotional responses and energy-rich foods, while bitterness often signals potentially harmful substances and elicits aversive reactions (Small, 2012). These contrasts provide a robust framework for investigating neuronal activation patterns related to taste perception and hedonic evaluation using functional near-infrared spectroscopy (fNIRS). The exclusion of salty, sour, umami, and fat tastes was a methodological decision aimed at reducing the complexity of the experimental design. Including all basic tastes would have required a much larger sample size to account for the variability in individual sensitivity and preference, which was beyond the scope of this initial study. Additionally, focusing on sweet and bitter tastes allows for a more controlled comparison of the neuronal responses to tastes with inherently positive and negative valences (van den Bosch et al., 2014).

Hence, in the present investigation, we combined sensory evaluation and neuromarketing using functional near-infrared spectroscopy (fNIRS) to explore the possible patterns of neuronal activation reflecting basic taste sensitivity and affective responses related to hedonic evaluation of food. Moreover, we expected to find a relationship between neuronal activation for basic tastes and neuronal activation related to hedonic evaluation of food.

Most neuromarketing studies investigating food perception have used neuroimaging techniques such as functional magnetic resonance imaging (fMRI), positron emission tomography (PET), and magnetoencephalography (MEG) (Minematsu et al., 2018). Functional magnetic resonance imaging (fMRI) is the best-known and frequently used

imaging technique for acquiring insight into the human brain (Mehlhose & Risius, 2021). Despite the superior spatial resolution offered by fMRI, its high cost, low temporal resolution, and restricted mobility represent challenges for many researchers (Almajidy et al., 2020). In addition, when using fMRI, it is necessary to hold the head strictly stationary, which prevents subjects from more natural and free tasting or ingestion of food and drinks (Minematsu et al., 2018). fNIRS uses near-infrared light to measure changes in the optical characteristics of tissues, notably the absorbance of the blood. The most significant chromophores or chemical groups that absorb light at particular wavelengths in healthy perfused tissue are cytochrome coxidase, oxygenated hemoglobin HbO2, deoxygenated hemoglobin Hb, and their combined hemoglobin HbT. These concentrations fluctuate with time and oxygen level (Almajidy et al., 2020).

Oxygen consumption increases as a result of increased cerebral blood flow (CBF) in active brain regions. These locations show a significant increase in oxyhemoglobin and decrease in deoxyhemoglobin as a result of the hemodynamic response (Meyerding & Mehlhose, 2020). This is similar to the blood oxygen level dependency (BOLD) principle used in fMRI measurements.

Based on the modified Beer-Lambert law, the optical data from fNIRS are transferred into oxygenated hemoglobin (OxyHb), deoxygenated hemoglobin (DeoxyHb), and total hemoglobin (totalHb) concentration changes as ΔOxyHb, ΔDeoxyHb, and ΔtotalHb, respectively, which are three parameters from fNIRS. Our investigations focused on OxyHb because it has the best connection with the blood oxygen level-dependent signal and is most sensitive to changes in regional cerebral blood flow (CBF) (Hu et al., 2013).

The development of functional near-infrared spectroscopy (fNIRS) systems, which offer a transportable and affordable imaging modality for cerebral hemodynamics, may help overcome these limitations (Almajidy et al., 2020). The portability and convenience of fNIRS makes it possible to utilize this technology widely, particularly in more realistic experimental situations where the test subjects must be able to move around more freely. It also has reduced sensitivity compared to other neuroimaging techniques, increasing its robustness against body movements and expanding its range of application to outdoor or unrestricted contexts. In addition, the fNIRS process is comparable to the BOLD signal concept utilized in fMRI measurements, allowing for a comparison between fNIRS and fMRI results (Mehlhose & Risius, 2021). This technique allows the subject to eat and drink without severe restrictions because the subject wears only a set of optodes consisting of emitters and detectors of near-infrared light; therefore, brain functions can be examined under relatively natural tasting conditions (Minematsu et al., 2018).

However, fNIRS spatial resolution is limited compared to that of fMRI signals. As the acronym suggests, fNIRS uses near-infrared light of wavelengths longer than visible at 750 nm–1200 nm and benefits from the particular optical properties of the tissue regarding this low-energy radiation (Almajidy et al., 2020). However, as fNIRS data are obtained on the head surface in the prefrontal cortex (PFC), it is not possible to measure the activity of deeper areas, such as the primary and secondary gustatory areas or the cingulate cortex and amygdala (Minematsu et al., 2018).

The overall aim of the present study is to combine sensory research with neuromarketing techniques like fNIRS to better understand consumer behavior and preferences through neuroimaging. Aligning with this aim, the following specific objectives provide a framework for the study:

- Ø Investigate the specific neuronal activation patterns in the prefrontal cortex in response to basic tastes (sweet and bitter) using functional near-infrared spectroscopy (fNIRS). This objective focuses on identifying and comparing the distinct brain activation signals elicited by the two basic tastes.
- Ø Analyze the relationship between innate sensitivity to basic tastes (sweet and bitter) and the hedonic preferences for food products. This includes examining whether individuals with a higher sensitivity to these basic tastes show different neuronal and subjective responses to hedonically different chocolates (whole-milk chocolate and dark chocolate).
- Ø Assess the feasibility of using fNIRS as a predictive tool for consumer preferences based on neuronal data. This entails evaluating whether the fNIRS measurements can reliably differentiate between "Likers" and "Dislikers" of various food products, particularly chocolates, and predict their overall liking.
- Ø Determine the extent to which subjective evaluations of taste and preference correlate with neuronal activation patterns observed during the tasting sessions. This involves a detailed analysis of the data collected from sensory questionnaires and fNIRS measurements to establish any significant associations.

2. Methods

In the present study, we used fNIRS to monitor neuronal activation in the prefrontal cortex in response to basic tastes (sucrose and caffeine solutions) and hedonically different food (two chocolate alternatives). Participants were asked to fill out a questionnaire to gather their subjective evaluations of the experimental stimulus.

The questionnaire for the sensory and fNIRS experiment was constructed to gather comprehensive data on participants' demographic details, general preferences, and specific sensory experiences during the experiment. The structure of the questionnaire begins with demographic questions, asking participants to indicate their gender identity, with options for female, male, and diverse, and to specify their age in years. Following the demographic section, the questionnaire includes general questions to assess participants' overall condition and dominant hand. Participants are asked whether they have slept sufficiently, with options to respond 'Yes' or 'No,' and whether they are right-handed, again with 'Yes' or 'No' as possible answers. During the experimental blocks, where participants taste various samples, the questionnaire is used to record their reactions. Each experimental block consists of five samples, each tasted five times. After each tasting, participants evaluate their overall liking of the sample using the same 7-point Likert scale. The scale ranges from "Missfällt mir sehr" (Dislike very much) to "Gefällt mir sehr" (Like very much), with intermediate options to capture varying degrees of preference. This part of the questionnaire is designed to capture immediate, specific reactions to each sample, allowing for a detailed analysis of sensory responses.

These participants were selected based on demographic (balanced gender) and physiographic criteria to ensure the validity and reliability of the results. Key exclusion criteria included any history of sensory, eating, neurological, or psychiatric disorders, as well as the use of medications that could interfere with taste perception. Additionally, participants were required to abstain from eating or drinking three hours before the experiment to avoid any potential influence on taste perception. Further refinement of the sample was done during the experiment. Three participants were excluded from the final analysis: one due to being left-handed, which can influence brain activation patterns, and two others due to unstable connection signals and event-related noise caused by temporal head movements. This led to a final sample size of 31 participants, comprising 16 women and 15 men.

Participants were required to abstain from eating or drinking for three hours before the start of the experiment. This precaution was implemented to ensure that the participants' sensory perception was not influenced by recent consumption of food or beverages. Food and drinks can leave residual tastes in the mouth, alter the sensitivity of taste receptors, and impact overall sensory evaluation (Iannario et al., 2012). Additionally, recent consumption can affect the blood flow and metabolism, which in turn could influence the fNIRS measurements of neuronal activity (van Rijn, de Graaf & Smeets, 2018). By enforcing a

fasting period, we aimed to standardize the participants' sensory state, thereby reducing variability and enhancing the reliability of the results.

Our first aim was to investigate possible brain activation patterns related to basic tastes (sweet and bitter) and hedonically different foods (the two chocolate alternatives). Furthermore, we explore the possible relationship between innate sensitivity to basic tastes and hedonic preferences for food products. For these purposes, we compared the neuronal activation for the experimental stimuli. Subsamples were then formed according to the participants' subjective evaluations of the questionnaires. The neuronal data of the subsamples were compared for subsequent analysis. The following section describes the fNIRS measurement and experimental procedure, and the methods for data analysis are also specified.

2.1. fNIRS measurement

In this study, we used the NIRSport 2 device (NIRx Medical Technologies). Optical signals were measured at wavelengths of 760 and 850 nm. Eight near-infrared light sources (diodes) and seven detectors (optodes) were built into the neoprene headband to create 22 measurement channels (see Fig. 1). To ensure the best possible light dispersion, optodes and diodes were arranged in a U-shape directly on the participant's forehead 3 cm apart (Laves et al., 2022). An exact placement of the optodes and diodes on the head is necessary to localize neural activity and create a map of the brain areas. Their location is specified by the international 10–20 system, a method for describing and localizing EEG scalp electrodes, with the aim of maintaining standardized study outcomes concerning the location of an electrode and the underlying area of the brain (Jurcak, Tsuzuki & Dan, 2007). The topographical layout and positions of the measurement channels for the PFC are shown in Fig. 1.

Psychopy software (version 2022.2.2) was used to set up the experimental design. For data acquisition, the NIRSport 2 instrument was used with the Aurora fNIRS software. Information regarding the experimental design (trigger signals) was automatically sent from Psychopy to Aurora.

2.2. Subjects

A total of 34 healthy adults were recruited to participate in the experiment, which was conducted between August 8th and August 31, 2022, in the sensory lab at HAW Hamburg. None of the participants used medications that interfered with taste or were free of sensory, eating, neurological, or psychiatric disorders. They were not permitted to eat or drink three hour before the start of the experiment. Participants were informed of the purpose and safety of the experiments, and written informed consent was obtained prior to participation in the experiment.

Informed consent was obtained from all participants involved in this experimentation/survey. Participants were fully informed about the nature, purpose, and potential risks of the study before providing their consent. They were assured that their participation was voluntary and that they could withdraw from the study at any time without any consequences. Confidentiality and anonymity of the data were maintained throughout the study. The study was approved by the ethic committee of the HAW Hamburg faculty of Life Sciences (Discovering Consumer Preferences for Food Products using fNIRS, Process no 2020–09).

2.3. Experimental procedure

Before beginning the experiment, the participants were informed in detail about the experimental design. Participants were invited to a quiet room with neutral light. A sensory cabinet was constructed for the experiments. We asked the subject to sit on a chair in front of the screen, which was installed with Psychopy software, and displayed the instructions of the experiment (see Fig. 2). Then, they were fitted with the fNIRS headband and asked to remain as calm as possible during the whole experiment and to avoid strong head movements. After preparing them with the headband, it was necessary to calibrate the detector gains in NIRStar for each subject to optimize the signal-to-noise ratio. The signal quality of the channels was checked before recording (Meyerding & Mehlhose, 2020).

2.4. Stimuli and experimental design

The experiment consisted of five conditions: tasting the five stimuli. We applied sucrose solution with a sweet taste threshold concentration of 0.576 g/100 ml as a slightly sweet stimulus and caffeine solution with a bitter taste threshold concentration of 0.0195 g/100 ml as a slightly bitter stimulus. In other words, some participants may not have recognized the taste of the solution. Two types of chocolates from Lindt were chosen as stimuli with a more complex flavor. One is whole milk chocolate, and the other is dark chocolate with 85 % cocoa. Filtered water was used as the neutral control stimulus. The experimental conditions are listed in Table 1.

The choice of chocolate as a stimulus in this study is rooted in its complex flavor profile and its widespread popularity, making it an ideal candidate for examining taste perception and hedonic evaluation. Chocolate offers a rich and varied sensory experience that includes

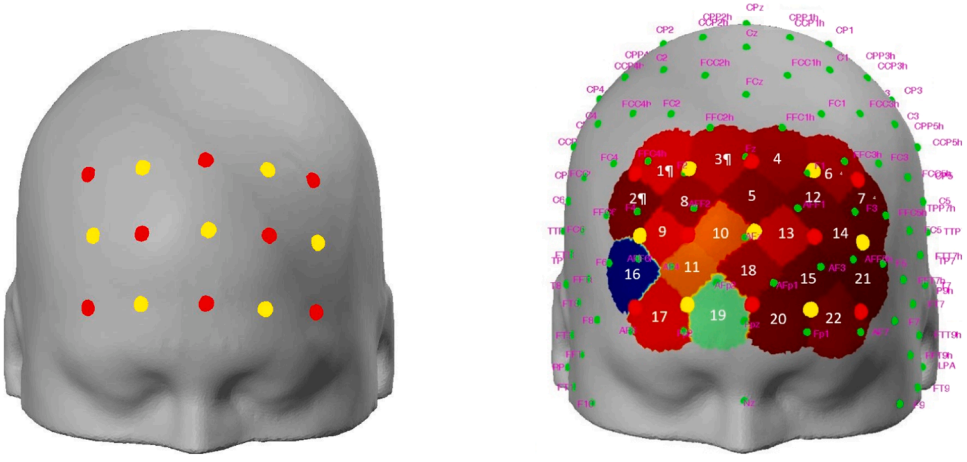

Fig. 1. Topographical layout of prefrontal cortex measurements (left).Positions of detectors (yellow points) and light sources (red points). The coverage of the headband was shown on the head model with EEG 10–20 reference points placement. Position of measurement channels (right). Adjacent sources and detectors resulted in one measurement channel (channels 1–22).
Note. Here, coloring has no meaning. Mapping out of nirsLAB.

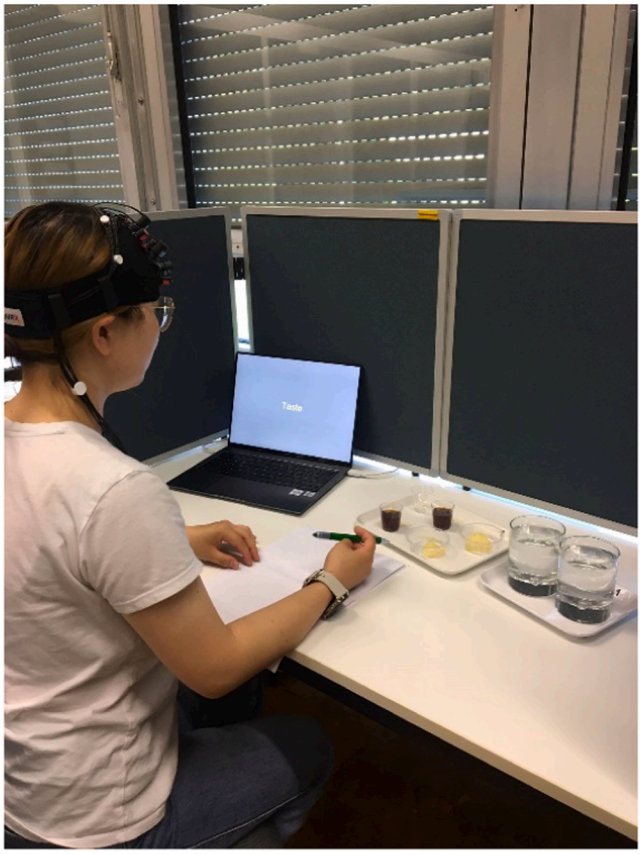

Fig. 2. Sensory cabinet for the experiment.

Table 1
Experimental Conditions.

Condition	stimuli	amount	abbreviation
1	Water	20 ml	C1: W
2	Sucrose solution	20 ml	C2: SS
3	Caffeine solution	20 ml	C3: CS
4	Whole milk chocolate	5 g	C4: MC
5	Dark chocolate	5 g	C5: DC

multiple taste components such as sweetness, bitterness, and creaminess. This complexity allows for a more nuanced analysis of how different taste elements are processed in the brain. Dark chocolate, with its high cocoa content, provides a strong bitter taste, while milk chocolate offers a sweeter, creamier flavor. This diversity in taste profiles makes chocolate a valuable stimulus for studying neuronal responses to different taste qualities (Drewnowski & Almiron-Roig, 2010). Additionally, it is widely liked and consumed, which makes it a relevant and relatable subject for participants in sensory studies. The hedonic response to chocolate is well-documented, with many studies highlighting its ability to evoke pleasure and reward. This widespread preference ensures that the findings of the study are applicable to a broad audience and relevant in real-world contexts (Parker, Parker & Brotchie, 2006). Chocolate is a good candidate for studying hedonic evaluation due to its ability to activate the brain's reward centers. The consumption of chocolate has been associated with the release of endorphins and dopamine, which contribute to its pleasurable effects. This makes it a suitable food item for examining how hedonic responses are reflected in neuronal activation patterns (Nehlig, 2013). Using chocolate as a stimulus allows for comparability with previous studies that have also employed chocolate to investigate taste perception and neural responses. This continuity helps to build on existing knowledge and contributes to a deeper understanding of the underlying mechanisms (Scholey & Owen, 2013; Small, 2010).

The tasting was carried out blindly, that is, the subjects knew that they would taste different types of edible solutions and chocolates but did not know the concentration of solutions, type, brand, or sequence of chocolates. The samples were individually stored at room temperature.

The experimental trial consisted of the following steps (see Fig. 3): the participants took a sample into the mouth within 8 s. For the liquid stimulus (water, sucrose solution, and caffeine solution), they had to drink 20 ml of each sample, swallow the sample for 5 s, and fast for 20 s. For the two chocolates, the participants had to take 5 g of each chocolate and then chew them slowly and gently to taste the flavor for 20 s, followed by a cue for swallowing for 5 s. After the experiment, participants filled out a questionnaire to evaluate the samples. For water, sucrose, and caffeine solutions, participants were asked if they recognized the taste of the stimulus. For water and the two chocolates, participants were asked to rate their overall liking on a 7-point hedonic scale from "dislike extremely" to "like extremely." The participants then rinsed their mouths to remove the remaining taste.

In one round, a participant tastes all samples (from conditions 1 to 5). This round was repeated five times, with a rest period of 20 s between each trial. During the rest period, the subject was asked to look at the laptop on the front and to restrain head movements.

2.5. Data analysis

2.5.1. Subjective ratings

The subjective ratings were analyzed using R Studio. The mean values of overall liking were compared between the conditions and between the taste discriminator groups using a single-factor analysis of variance (ANOVA). Statistical significance was set at $p < 0.05$.

2.5.2. fNIRS data

fNIRS data acquired by Aurora were preprocessed and analyzed using nirsLAB (version 2019.4). The data were loaded into the nirsLAB software. Different conditions were denoted, and their durations were specified as 20 s for each condition. Responses to swallowing, rinsing, and rating were not used in further analyses.

First, the data were preprocessed to obtain better quality data. To smooth the raw data, a band-pass filter (high/low frequency filter of 0.01–0.2 Hz) was applied to control for possible artifacts (e.g., movement, heartbeat) that might interfere with the measurement of the intended effects. Then, the concentrations of OxyHb and DeoxyHb were detected by applying a modification of the Beer-Lambert law to the raw data of the 22 channels (Laves et al., 2022). We chose the OxyHb values for further analysis because they have the best connection with the blood oxygen level-dependent signal and are most sensitive to changes in regional cerebral blood flow (CBF) (Hu et al., 2013).

The analysis consisted of statistical parametric mapping (SPM) levels 1 and 2. First, in the SPM Level 1 step, the data were analyzed for each subject individually. For each participant, a General Linear Model (GLM) was used to show how neuronal activity changed over time during the experiment (Laves et al., 2022). After estimating the general linear model coefficients, the significant single-subject SPM results for neuronal activity in the PFC were compared among the different conditions. The differences between the conditions were measured with a one-sided *t*-test, which depends on the calculated Betas (magnitudes for each regressor), variance/standard deviation, and degrees of freedom. The *t*-test uses an estimate of the standard deviation across time. The significance level was set at 5 % (p-value < 0.05). In addition to the results for individual participants, it is necessary to generalize the results to assess group-level differences in prefrontal brain activation.

Therefore, the individual contrast images were used for the next step, the analysis of SPM Level 2, to measure significant differences in neuronal activity between conditions at the group level. The differences were also measured with a one-sided *t*-test, but different from the level 1

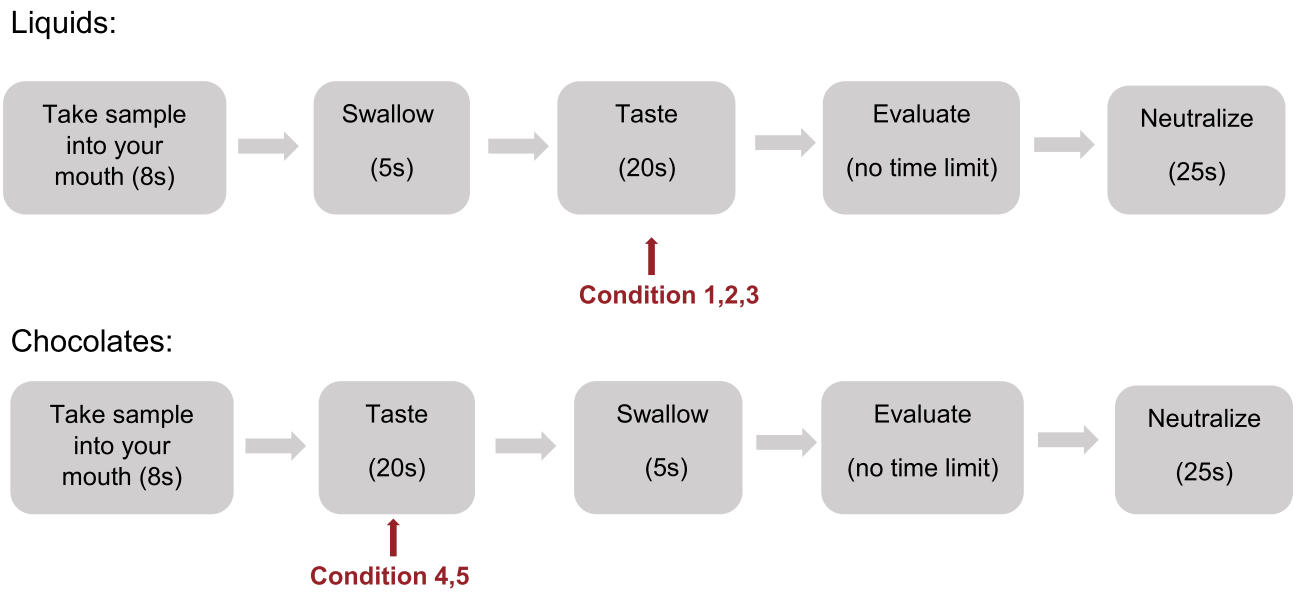

Fig. 3. Schematic of experimental design.

t-test, a level 2 *t*-test use the standard deviation across subjects (Meyerding & Risius, 2018). The results were visualized in brain images of different colors. In the nirsLAB color code, red indicates a positive t-value and, therefore, a strong activation.

3. Results

3.1. Sample description

A total of 34 participants, including 17 women and 17 men (aged 18 to 60 years) participated in the experiment. We excluded the tasting data of three participants. One because he was left-handed, and the other two because of unstable connection signals and event-related noise due to temporal head movements. The final sample comprised 16 women and 15 men.

3.2. Subjective evaluation of the stimuli

3.2.1. Basic taste recognition

Fifteen participants (48.39 %) recognized the sweet taste during tasting of the sucrose solution. For the caffeine solution, only nine participants (29.03 %) recognized a bitter taste. Four subsamples (Table 2) were formed for the subsequent analysis.

3.2.2. Subjective hedonic evaluation of the chocolates

Participants rated their overall liking of the water sample and the two chocolate alternatives using a 7-point hedonic scale. The water sample had a moderate overall rating of 4.7, which confirmed a neutral taste. The whole milk chocolate obtained the best overall liking of 5.3, while the bitter chocolate obtained the worst overall liking of 3.6, which was significantly lower than the other two samples ($p < 0.05$) (see Fig. 4).

Table 2
Grouping according to the basic taste recognition of sucrose and caffeine solutions.

Group	Description	Subsample size
Group 1	Sweet taste recognized	15
Group 2	Sweet taste not recognized	16
Group 3	Bitter taste recognized	9
Group 4	Bitter taste not recognized	22

Groups were also formed based on the overall likings of the two chocolate alternatives. We considered the participants as "Liker," who rated the sample greater than 4.0. The participants who rated the sample <4.0, were considered as "Disliker." Ratings equal to 4.0 were excluded from the grouping (4.0, deliberately not considered, as it represented a neutral rating).

Two additional subsamples were formed for analysis (see Table 3). The participants who rated the whole milk chocolate greater than 4.0, and rated the dark chocolate <4.0, were identified as group 5 (whole milk chocolate liker and dark chocolate disliker). In contrast, the participants who rated the whole milk chocolate <4.0 and rated the dark chocolate greater than 4.0, were selected in group 6 (whole milk chocolake dislikers and dark chocolate likers).

3.3. fNIRS data analysis

3.3.1. SPM level 1

In the analysis of SPM level 1, we calculated the differences in neuronal activation in the PFC between conditions (C1 vs. C2, C1 vs. C3, C2 vs. C3, C1 vs. C4, C1 vs. C5, and C4 vs. C5). All the subjects showed significant activation of these contrasts. However, the activation varied between subjects.

3.3.2. SPM level 2

3.3.2.1. Analysis for the whole group. Conditions vs. baseline

First, the neuronal activity (presented by OxyHb concentration) of each experimental condition during the tasting phase was compared with the results from the baseline (see Fig. 5). Baseline was defined as hemodynamic data during the break phase with no movement from the participants. A *t*-test was used to measure the significance of the differences. The threshold was set at $p < 0.05$. The channels with significantly altered activity are listed in Table 4.

Significantly increased activity was detected in channels 2 and 21 for all five contrasts. Activity in channel 22 also significantly increased, except when tasting whole milk chocolate. Significantly decreased activity was detected in channel 15 for all five contrasts. The activity in channel 18 also significantly decreased, except when sucrose solution was tasted. In Channel 1, we detected significantly increased activity during the chocolate task.

Conditions vs. water

Second, the neuronal activity of the sucrose solution, caffeine

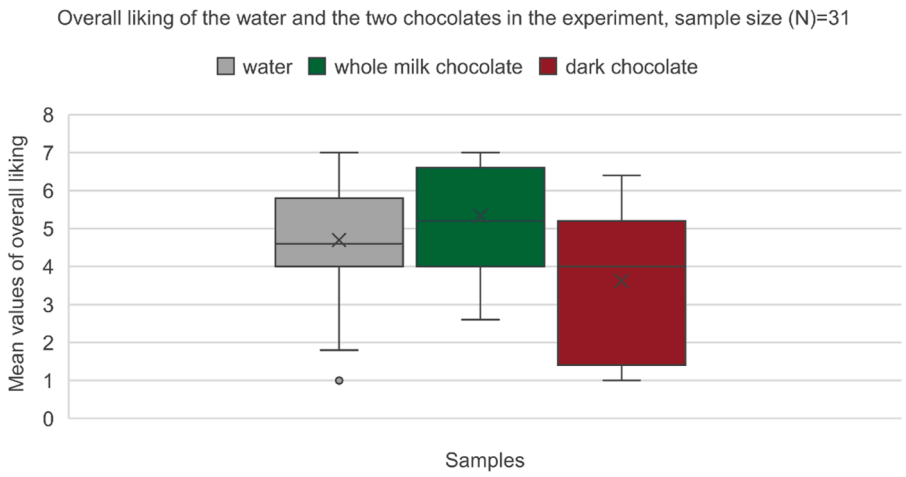

Fig. 4. Hedonic evaluation of water and two chocolates.
Note. The participants evaluated each sample five times on a scale from 1 (extremely dislike) to 7 (extremely like), sample size $N = 31$.

Table 3
Grouping according to the taste discrimination of the two chocolates.

Group	Description	Subsample size	Mean values of overall liking
Group 5	Whole milk chocolate likers & Dark chocolate disliker	13	Whole milk chocolate: 6.2 Dark chocolate: 1.8
Group 6	Whole milk chocolate dislikers & Dark chocolate likers	4	Whole milk chocolate: 3.5 Dark chocolate: 5.4

solution, and the two chocolates were compared with the neutral condition (water), but no significant differences were detected at the group level (SPM 2).

Conditions vs. *conditions*

With regard to the comparison of the two basic taste conditions ("Sucrose solution" vs. "Caffeine solution) and of the two chocolate conditions ("Whole milk condition" vs. "Dark chocolate"), no significant differences in the neuronal activity were detected on group level (SPM 2).

3.3.2.2. Analysis based on the subsamples. We created the contrast [condition baseline] for each subsample and compared this contrast between different samples using F-test statistics.

Basic tastes recognition and neuronal activity

First, we directly compared the contrast [SS-BL] of Group 1 (sweet taste recognized) and the contrast [CS-BL] of Group 3 (bitter taste recognized) (see Fig. 6). Significantly increased neuronal activity in channels 21 and 22 (OFC) was detected in both contrasts. In group 1, for the subjects who recognized the sweet taste, neuronal activity was significantly decreased in channels 15 and 19 (PFC) (see Fig. 6, A). In contrast, in group 3, for the subjects who recognized the bitter taste, neuronal activity was significantly increased in channels 2, 4, 6, 10, and 20 (see Fig. 6, B).

We then compared the neuronal activity between the subjects who recognized the basic taste and those who did not recognize the basic taste for the two solutions (see Fig. 7). From a direct comparison between A and B, we observed a common increase in neuronal activity in Channels 21 and 22. In addition to channels 21 and 22, activation in the opposite direction was detected between the subjects who recognized the sweet taste (decreased) and those who did not recognize (increased)

Table 4
Channels with significantly changed OxyHb concentrations compared to the experimental conditions at baseline.

Contrast	Channels with significantly increased OxyHb	Channels with significantly decreased OxyHb
Water > Baseline	2, 21, 22	15, 16, 18, 19
Sucrose solution > Baseline	2, 9, 21, 22	15, 16, 19
Caffeine solution > Baseline	2, 9, 11, 21, 22	15, 16, 18,
Whole milk chocolate > Baseline	1, 2, 21	6, 15, 18
Dark chocolate > Baseline	1, 2, 21, 22	15, 12, 18, 19

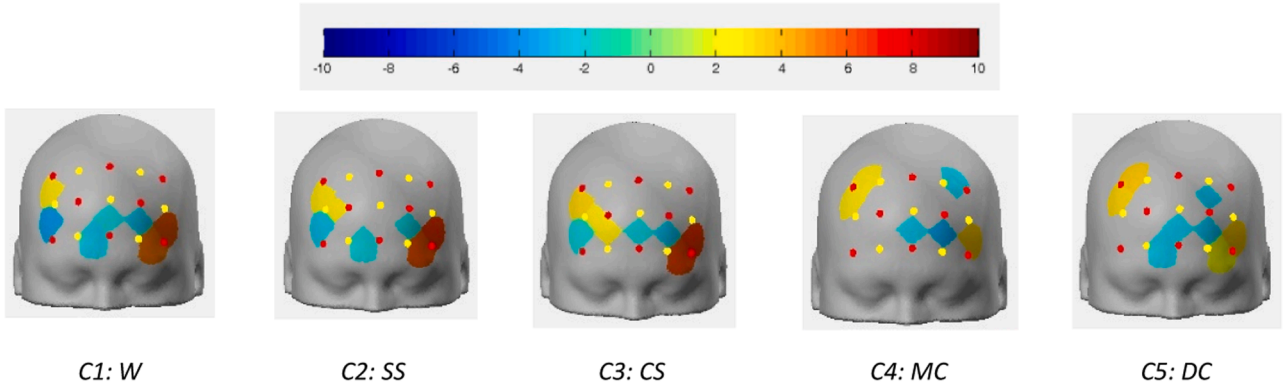

Fig. 5. Significant neuronal activation in experimental conditions in comparison to baseline.

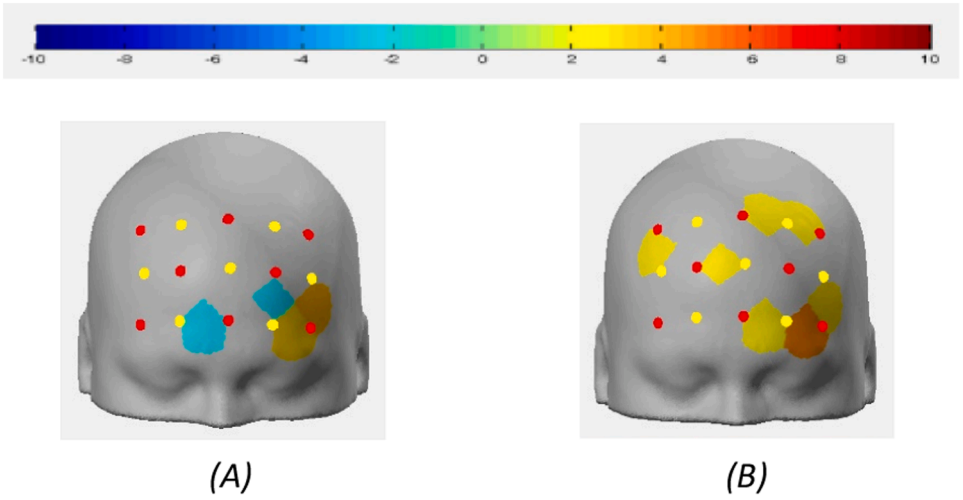

Fig. 6. Significantly increased and decreased neuronal activity for the contrast [SS-BL] of group 1 (sweet taste recognized) in (A) and for the contrast [CS-BL] of group 3 (bitter taste recognized) in (B). The activation threshold was set at $p < 0.05$.

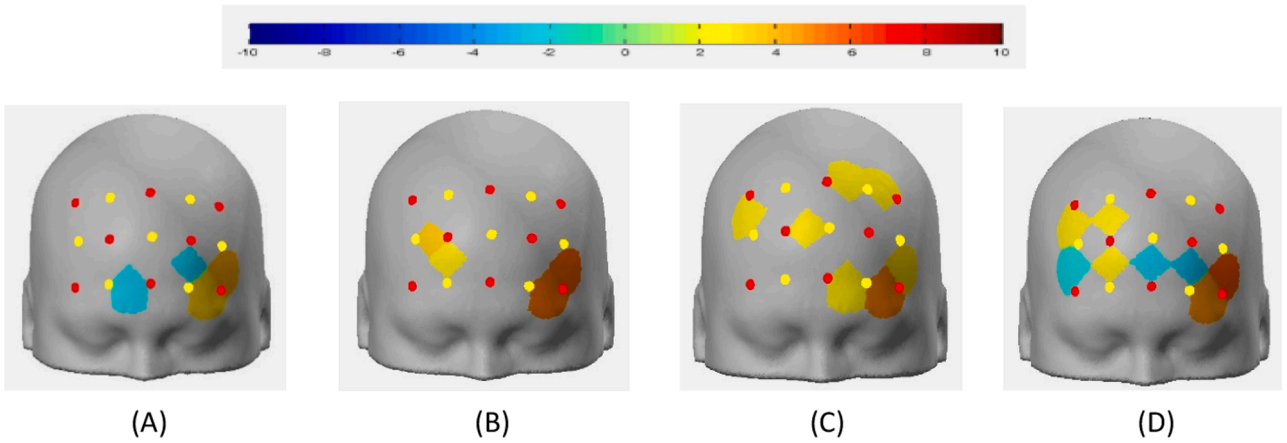

Fig. 7. Significantly increased and decreased neuronal activity was observed for the contrast [SS-BL] of group 1 (sweet taste recognized) in (A), for [SS-BL] of group 2 (sweet taste not recognized) in (B), for [CS-BL] of group 3 (bitter taste recognized) in (C), and for [CS-BL] of group 4 (bitter taste not recognized) in (D). The activation threshold was set at $p < 0.05$.

the sweet taste. We did not find consistent results in the direct comparison of C and D. The significance of the difference between A and B, C, and D was analyzed using the F-test; however, no significant difference was detected.

Next, we compared the neuronal responses to whole milk chocolate between groups 1 and 2. Similarly, the responses to dark chocolate

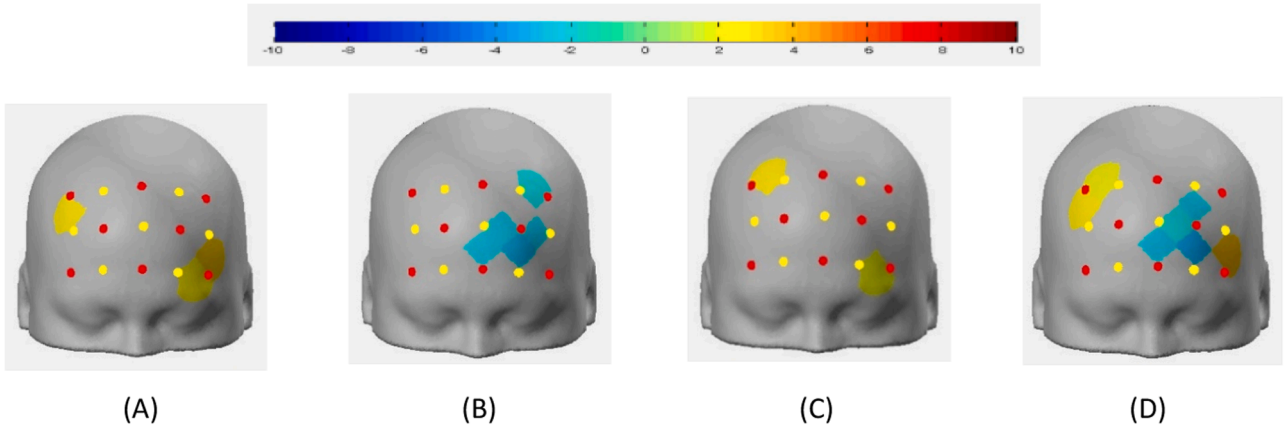

Fig. 8. Significantly increased and decreased neuronal activity was observed for the contrast [MC-BL] of group 1 (sweet taste recognized) in (A), for [MC-BL] of group 2 (sweet taste not recognized) in (B), for [DC-BL] of group 3 (bitter taste recognized) in (C), and for [DC-BL] of group 4 (bitter taste not recognized) in (D). The activation threshold was set at $p < 0.05$.

between Groups 3 and 4 were also compared (see Fig. 8). With regard to the whole milk chocolate, significantly increased activity was detected in group 1 in channel 2, 21, 22. On the contrary, decreased activity was detected in group 2 in channel 6, 13, 14, 15, 18. Similarly for the dark chocolate, the neuronal activity increased both in group 3 and 4 in channel 2 and 22, but also decreased activity was detected in group 4 in channel 12, 13, 15, 18. This result may suggest that subjects who recognized the basic tastes revealed an increased activity caused by matching the chocolate condition (see Fig. 8, A and C), while subjects who did not recognize the basic tastes mainly revealed a decreased activity by matching the chocolate condition (see Fig. 8, B and D).

Overall liking and neuronal activity

In this step, differences in neuronal activity between Likers and Dislikers for the two chocolates were investigated (Fig. 9). In group 5, formed with MC-liker and DC-disliker, the two chocolates both significantly increased neuronal activity in channel 2, and significantly decreased neuronal activity in channels 15 and 20 (see Fig. 9, A and B), and the dark chocolate also increased neuronal activity in channel 1 (see Fig. 9, B). In group 6, formed with MC-disliker and DC-liker, both chocolates significantly decreased neuronal activity in channels 16, 17, and 19 (see Fig. 9, B and D).

The significance of the difference between A and C for the whole milk chocolate and between B and D for the dark chocolate was analyzed using the F-Test (see Fig. 10). Significant differences in activation in channels 15 and 16 were detected between A and C (see Fig. 10), and in channels 2 and 16 were detected between B and D (see Fig. 10). Both chocolates caused significant differences in the activation of Channel 16 between the Likers and Dislikers. For whole milk chocolate, Likers showed a higher activation than Dislikers, but for dark chocolate, Disliker showed a higher activation than Likers.

3.4. Regression analysis for fNIRS data and overall liking

Stepwise regression analysis for channel-Betas and overall liking of the two chocolates was performed to investigate the possible relationship between neuronal activity and hedonic response to food. The aim of this analysis is to develop a prediction model for consumer and food preferences based on fNIRS data. The results show that for whole milk chocolate, channel 4 (std.Beta: 0.456, $p = 0.023$) and channel 6 (std. Beta: -0.440, $p = 0.028$) were included in the final prediction model. For dark chocolate, channel 2 (std. Beta: -0.548, $p = 0.003$), and channel 5 (std. Beta $= 0.427$, $p = 0.017$) were included in the final prediction model.

4. Discussion

This study aimed to explore the neuronal reflection in the human brain corresponding to sensory evaluation, specifically, the recognition of basic tastes (slightly sweet solution and slightly bitter solution) and preferences towards complex tastes (whole milk chocolate and dark chocolate). Brain activation was measured using fNIRS, which measures hemodynamic responses within the brain in a noninvasive manner and does not require fixation of the head and body. We combined sensory consumer tests and neuroimaging measurements to gain a better understanding of consumer decision making regarding food choices. We also sought to demonstrate the possibility of applying neuroimaging with fNIRS in future sensory and marketing research.

All five experimental conditions significantly induced brain activation across all subjects. For the neuronal response to basic tastes, we observed that sweet and bitter tastes tend to elicit decreased and increased neuronal activity, respectively. This result is consistent with previous studies (Bembich et al., 2010; Minematsu et al., 2018) that sweet tastes corresponding to pleasant emotions tend to elicit decreased neuronal activity, whereas bitter tastes corresponding to unpleasant emotions tend to elicit increased neuronal activity. Moreover, we pioneered the discussion on taste sensitivity reflected by neuronal data. However, no significant differences in neuronal activation related to different sensitivities to basic tastes were observed. However, it is interesting that subjects who recognized the basic tastes revealed increased activity caused by matching chocolate conditions. In contrast, subjects who did not recognize the basic tastes revealed decreased activity by matching the chocolate condition. This suggests that basic taste sensitivity is correlated with hedonic responses to foods that are dominated by this basic taste. This innovative finding indicates that the use of fNIRS to explore taste sensitivity may be useful and promising for gaining a deeper understanding of consumer preferences.

We investigated the differences in fNIRS data between Likers and Dislikers when tasting the two chocolate alternatives. We found that both chocolates caused significant differences in activation in channel 16 between Likers and Dislikers, but we did not find a consistent neuronal activation pattern to distinguish between Likers and Dislikers for complex food products. Our results indicate that this area is crucial for investigating consumer food preferences. However, it may be difficult to discriminate between the Likers and Dislikers of different foods with a single activation pattern.

The brain is complex and food-related decision-making processes are multidimensional. A better understanding of this process may provide more opportunities to understand and influence consumer behavior. Therefore, it has the potential to affect obesity, health, and environmental and climate crises. The present study demonstrated that the

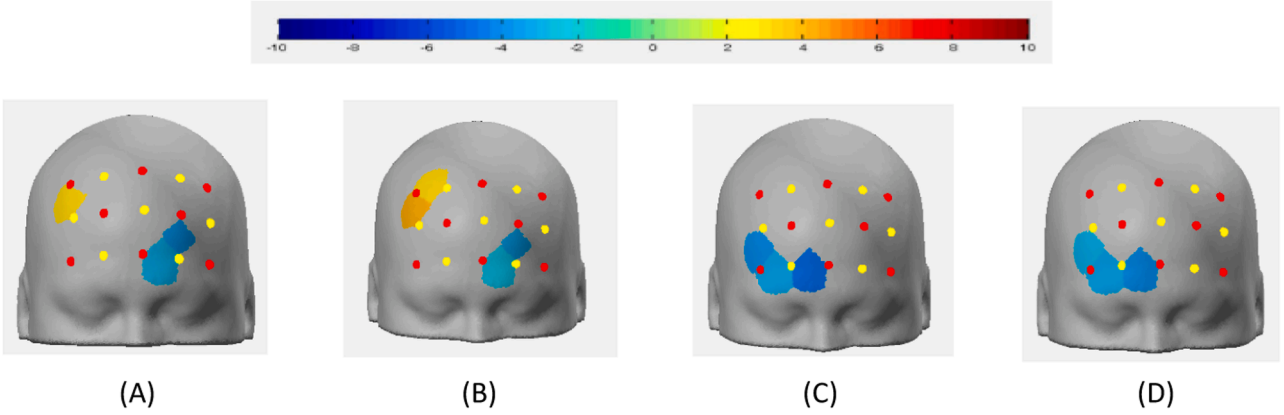

Fig. 9. Significantly increased and decreased neuronal activity for the contrast [MC-BL] of group 5 (MC-liker and DC-disliker) in (A), for [DC-BL] of group 5 (MC-liker and DC-disliker) in (B), for [MC-BL] of group 6 (MC-disliker and DC-liker) in (C), and for [DC-BL] of group 6 (MC-disliker and DC-liker) in (D). The activation threshold was set at $p < 0.05$.

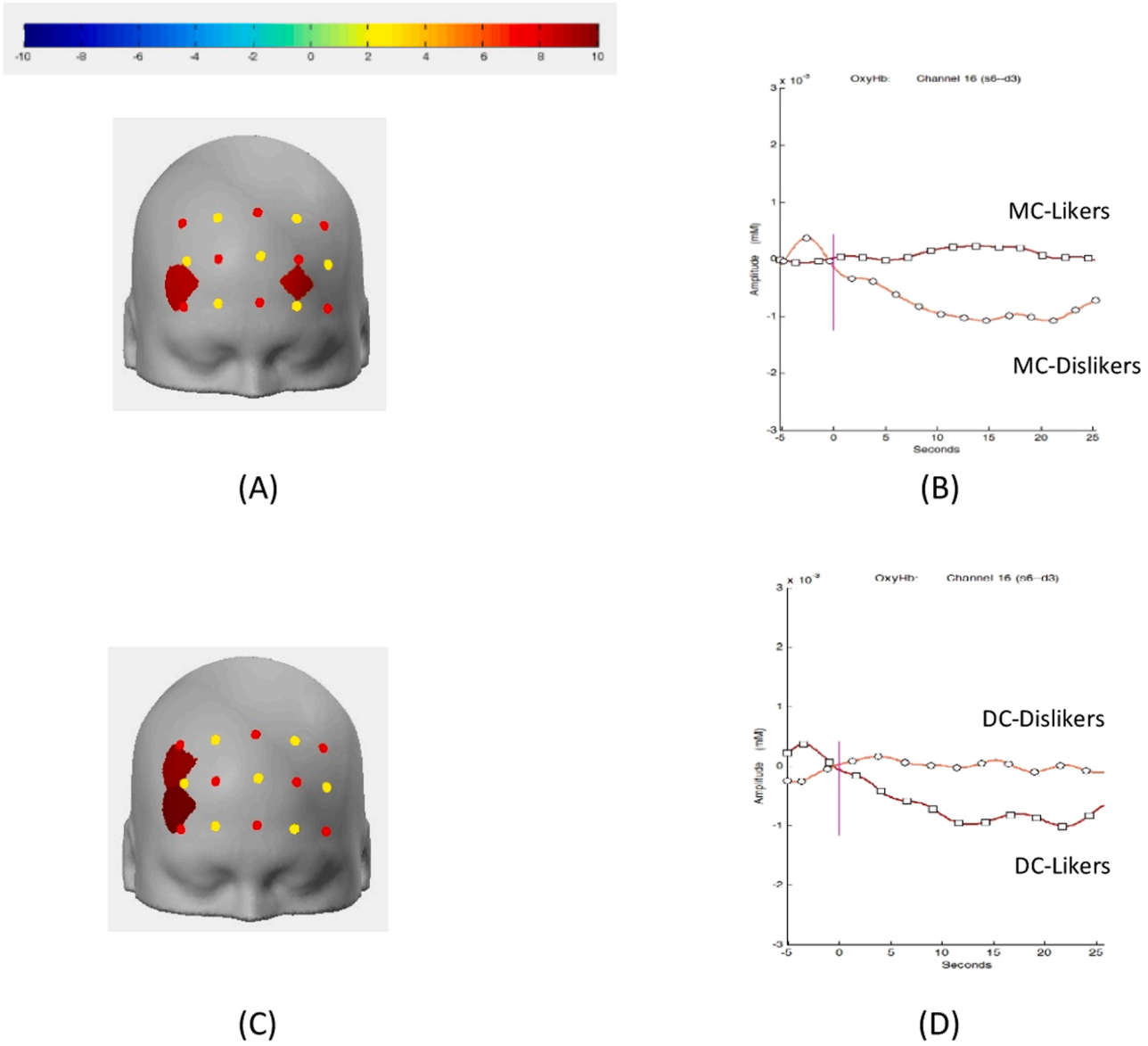

Fig. 10. Significant difference in neuronal activation between Likers and Dislikers for whole milk chocolate (A), comparison of the time courses of OxyHb from channel 16 between Likers and Dislikers for whole milk chocolate (B); significant difference in neuronal activation between Likers and Dislikers for dark chocolate (C), comparison of the time courses of OxyHb from channel 16 between Likers and Dislikers for dark chocolate (D). The activation threshold was set at $p < 0.05$.

fNIRS assessment may be able to visualize neuronal activation for food-related decision-making processes, so that it is promising to add value to traditional marketing research and sensory research. Our findings may provide a foundation for future studies that combine neuroimaging with consumer sensory research to gain a deeper understanding of food-related decision-making.

4.1. *Different activation patterns between subjects*

As mentioned above, it is generally accepted that the PFC is involved in higher-order functions such as emotion, cognition, memory, and decision-making. It is less probable that the subject only focuses on flavor in the mouth without thinking of anything else during the entire period of tasting (Minematsu et al., 2018). If the PFC is concerned with mental processing that accompanies self-generated thoughts, ongoing taste stimuli may have induced various spontaneous thoughts, resulting in variability in PFC activation among subjects. Besides hedonic tone to the stimulus (pleasant or unpleasant), other emotions, such as happiness, curiosity, inspiration, depression, liking, wanting, and appetite, might occur with different degrees in the subjects and may also be associated with hemodynamic changes (Minematsu et al., 2018). Therefore, brain activation in the subjects varied.

4.2. *Different activation patterns for different stimuli*

All five experimental conditions caused significant brain activation across all subjects. Common negativ brain activation was observed in aPFC (channel 15) and positiv activation in OFC (channel 21, 22). The baseline in our study was a resting activity rather than an activity elicited by a tasteless solution. This may imply that this part of the brain is active when stimuli was “tasted” in the mouth regardless of whether the stimuli has taste or not. The PFC has been implicated in many other functions, including integration of sensory information with the control of oral movements (Okamoto et al., 2009). This common brain activation may be associated with oral movements.

Interestingly, water, sucrose solution, and caffeine solution revealed similar activation patterns, while the two chocolates revealed another similar activation pattern. This result may suggest that whether the

stimulus is liquid or solid has an important effect; in other words, the physicochemical properties of the stimulus may also be important in changing the OxyHb concentration. Van Rijn et al. (2018) suggested differential effects of selective attention on brain activation during tasting. That is, whether the subjects pay attention to recognize the basic taste or to their hedonic preference towards the stimulus, may cause different activation in the brain. However, in our study, the participants were instructed to recognize the basic taste of the stimulus or evaluate the overall liking of the stimulus after they finished tasting the stimulus; therefore, we assume that different activation patterns resulting from selective attention during tasting may be less probable in the present study.

4.3. Taste sensitivity and neuronal activity

The results of the test for the recognition of sweet and bitter tastes showed that only 48 % of the participants recognized the sweet taste and 29 % recognized the bitter taste. Participants showed different sensitivities to sweet and bitter tastes. We hypothesized that different basic tastes would cause different activation patterns in the PFC. To test this hypothesis, we compared the neuronal activity (subtracted baseline) between subjects who recognized the sweet taste and those who recognized the bitter taste directly. Activations in the opposite direction were detected: significantly decreased activity across the subjects who recognized the sweet taste, while significantly increased activity was observed across the subjects who recognized the bitter taste. This result is consistent with previous studies (Bembich et al., 2010; Minematsu et al., 2018) that sweet tastes corresponding to pleasant emotions tend to elicit decreased neuronal activity, whereas bitter tastes corresponding to unpleasant emotions tend to elicit increased neuronal activity.

In addition, we expected to see different brain activation between subjects who recognized the basic tastes and subjects who didn't recognized the basic tastes. This is of interest for the future use of fNIRS to detect taste sensitivity, for example, in sensory panel training. From the direct comparison of the neuronal activity between the subjects who recognized the sweet taste and subjects who did not recognize the sweet taste, we observed a decreased OxyHb in the aPFC across subjects who recognized the sweet taste and an increased OxyHb in the aPFC across subjects who did not recognize the sweet taste. On the contrary, OxyHb was increased in the aPFC across subjects who recognized bitter taste. However, it is possible that the neuronal activation differences here are the result of hedonic emotional changes caused by tasting sweet or bitter flavors instead of taste sensitivity. As discussed above, the sweet taste corresponds to a pleasant emotion leading to decreased OxyHb in the PFC and bitter taste corresponds to an unpleasant emotion leading to an increased OxyHb in the PFC. In contrast, qualitative and quantitative aspects of taste are generally accepted to be processed in deeper or more complex regions of the brain, such as the operculum and insula, representing the primary cortical gustatory area (Minematsu et al., 2018). However, fNIRS cannot measure the activity of deeper areas in the brain. Therefore, the use of fNIRS to detect taste sensitivity needs to overcome the influence of food-related emotional changes, which is a difficult problem.

In addition, we found that subjects who recognized basic tastes revealed increased activity caused by matching chocolate conditions. In contrast, subjects who did not recognize the basic tastes revealed decreased activity by matching the chocolate condition. In other words, subjects with higher sensitivity to the basic taste seem to show increased activation when tasting food dominated by this basic taste. As mentioned above, unpleasant food-related emotions lead to increased neuronal activation. This suggests that basic taste sensitivity is negatively correlated with hedonic responses to foods dominated by this basic taste.

4.4. Food preference and neuronal activity

The results from the sensory preference tests showed that the subjects significantly preferred the taste of whole milk chocolate (overall liking: 5.6) over the taste of dark chocolate (overall liking: 3.7) ($p < 0.05$). Water was characterized as having a neutral taste (overall liking). Unfortunately, contrary to our expectations, we did not observe a significant difference in neuronal activity between the three experimental conditions at the group level for all subjects.

Subjective flavor preferences result from a multitude of intrinsic and extrinsic factors (Bosch et al., 2014). The stimulus is a complex combination of different tastes, which is not a simple signal of either energy or toxic content, but rather requires a cognitive approach integrating the different taste qualities with personal experience, such as previous exposure and acquired preferences, product knowledge, and social context. This preference formation process is thought to occur through associative learning. For example, some subjects mentioned that after testing the dark chocolate, they immediately associated it with health snacks that contained more cocoa and less sugar, although the bitter taste was unpleasant. This cognitive modulation is complex and elicits multiple activations in the brain, not simply caused by the emotion of liking or disliking. Bosch et al. (2014) suggested that the difference between liking and disliking a learned preference of a complex taste is less pronounced than the difference in liking between innately preferred and unpreferred tastes (Bosch et al., 2014).

Regarding the comparison of taste discriminator groups, we investigated the difference in neuronal activation patterns between Likers and Dislikers when tasked with the same stimulus. In contrast to the comparison above, in this analysis, we held consistent intrinsic product properties and compared them with those of whole milk chocolate and dark chocolate. We found that both chocolates caused significant differences in the activation of channel 16 between the Likers and Dislikers, but with opposite activation patterns. For whole milk chocolate, Likers had a relatively stable OxyHb concentration, which slightly increased, while Dislikers showed a significantly decreased OxyHb concentration. Likers showed higher activation than dislikers did. In contrast, for dark chocolate, Likers had a significantly decreased OxyHb concentration, while Dislikers showed a slightly increased OxyHb concentration, and Likers showed a lower activation than Dislikers. Therefore, we did not find a consistent neuronal activation pattern to distinguish between Likers and Dislikers for complex food products. The reason may be that these two chocolates have very different physical properties; the whole milk chocolate is dominated by a sweet taste, while dark chocolate is dominated by a bitter taste. As discussed above, these two basic tastes would lead to neuronal activation in opposite directions. Based on this explanation, there may be different activation patterns to distinguish between Likers and Dislikers for whole milk chocolate and dark chocolate, respectively. It may be difficult to discriminate between the Likers and Dislikers of different foods with a single activation pattern.

In order to understand the relationship between neuronal activity and food preference, to investigate the possibility of using fNIRS to predict consumer response to particular food, we conducted a regression analysis between fNIRS data (channel Betas) and overall liking for the two chocolates. We found that channel 4 is positively correlated and channel 6 is negatively correlated with the overall liking of whole milk chocolate. For the dark chocolate, channel 5 was positively correlated, whereas channel 2 was negatively correlated with overall liking. As the above-mentioned discussion to the different activation patterns for two chocolate alternatives, we did not find a consistent conclusion for the relationship between neuronal data and preference for the two chocolate alternatives, which have very different physical properties. Minematsu et al. (2018) observed a negative correlation between the pleasant score and OxyHb level across channels in eight subjects by analyzing the mean correlation coefficients. Our results suggest that it may be possible to use fNIRS data to predict consumer food preferences. For a better understanding of this aspect, research with a larger sample size is

required.

4.5. Biochemical mechanisms of taste perception and hedonic evaluation

In the present study, we employed functional near-infrared spectroscopy (fNIRS) to investigate neuronal activation in the prefrontal cortex in response to basic tastes (sweet and bitter) and hedonically different chocolates (whole-milk and dark chocolate). While our primary focus was on the neuroimaging results, it is crucial to discuss the biochemical underpinnings that may explain the observed changes in parameters, particularly in the context of taste perception and neural activation.

Sweet taste perception is primarily mediated by G-protein-coupled receptors (GPCRs), specifically the T1R2 and T1R3 receptors, which are activated by sugars and artificial sweeteners (Nelson et al., 2001). When a sweet substance binds to these receptors, it triggers a signaling cascade involving the activation of adenylate cyclase and the subsequent increase in cyclic AMP (cAMP) levels. This leads to the opening of ion channels, causing cell depolarization and neurotransmitter release (Margolskee, 2002). The resultant signaling not only affects the gustatory pathways but also modulates brain regions involved in reward processing, such as the prefrontal cortex. This biochemical response explains the decreased neuronal activity observed in our study, as sweet tastes typically induce pleasurable and rewarding sensations, which are processed as less cognitively demanding (Small, 2012).

Bitter taste perception is mediated by a different set of GPCRs, known as T2R receptors. These receptors detect a wide variety of bitter compounds, which can signal the presence of potentially harmful substances (Chandrashekar et al., 2000). Activation of T2R receptors leads to a different signaling cascade that involves the phospholipase C (PLC) pathway, resulting in the production of inositol trisphosphate (IP3) and the release of intracellular calcium stores (Zhang et al., 2003). The increased intracellular calcium levels cause cell depolarization and neurotransmitter release, which activate neural circuits associated with aversion and caution. This biochemical response aligns with the increased neuronal activity observed in our study, as bitter tastes are processed with higher cognitive and emotional involvement due to their association with potential danger (Small, 2012).

The hedonic evaluation of food, such as chocolate, involves complex interactions between taste perception and the reward system in the brain. Chocolates, especially those high in sugar and fat, can stimulate the release of neurotransmitters like dopamine in the brain's reward centers (Smit & Blackburn, 2005). This response is particularly strong for sweet and creamy whole-milk chocolate, which explains the positive neuronal activation observed in "Likers" of this type of chocolate. Dark chocolate, with its higher cocoa content and bitter compounds, engages both the reward and aversion pathways. The complex flavor profile of dark chocolate involves a balance between bitter and sweet tastes, leading to more varied neuronal responses. The presence of flavonoids and other bioactive compounds in dark chocolate can also modulate brain activity by influencing neurotransmitter systems and providing neuroprotective effects (Nehlig, 2013).

Individual differences in taste receptor expression and sensitivity can significantly influence taste perception and hedonic evaluation. Genetic variations in taste receptor genes, such as TAS1R and TAS2R, can lead to differences in taste sensitivity and preferences. For example, variations in the TAS2R38 gene have been linked to differences in sensitivity to bitter compounds like PROP (propylthiouracil), affecting individuals' liking for bitter foods (Kim & Drayna, 2004). These genetic and biochemical differences help explain the variability in neuronal activation patterns observed in our study. Participants with higher sensitivity to sweet or bitter tastes may exhibit stronger and more distinct neuronal responses, reflecting their individual hedonic experiences (Han et al., 2020).

4.6. Limitations

While our study provides significant insights into the neuronal mechanisms underlying taste perception and consumer preferences, it is important to recognize several limitations. The primary limitation is the relatively small and homogenous sample size, which included only 31 participants after exclusions. This sample size may limit the generalizability of our findings to the broader population. Future studies should aim to include a larger and more diverse cohort to validate our results and improve the robustness of the conclusions.

Another limitation is the variability in taste sensitivity and preference among participants, which could have influenced the neuronal responses observed. Although we controlled for certain demographic factors, there are inherent individual differences in sensory perception that were not fully accounted for. Additionally, the exclusion of participants with neurological or psychiatric disorders, or those taking medications that could affect taste perception, may limit the applicability of our findings to these populations. Furthermore, we did not limit the age, gender, educational background, and dietary habits of the participants, so the intrinsic characteristics may vary among subjects, which also have a crucial effect on the hedonic response to food (Bosch et al., 2014). To overcome these possible confounding factors in future research, the sample should be homogeneous in terms of age, sex, educational background, and dietary habits. Regarding the research on basic taste sensitivity, we provide the first insights into the application of fNIRS to measure taste sensitivity. In future research on this topic, it would be beneficial to organize a trained sensory panel for the experiment, because they may have a more accurate response to the taste with slightly varying concentrations.

Standard sensory science methodology was not strictly adhered to, which may impact the reproducibility and robustness of the findings. Traditional sensory evaluations involve the use of trained panels and standardized procedures to minimize variability and enhance reliability (Iannario et al., 2012). Individual differences in taste sensitivity and preference among participants were not fully accounted for, which could have influenced the observed neuronal responses. Standard sensory science methodologies typically involve more rigorous controls for such individual differences, including pre-screening for taste sensitivity and employing a trained sensory panel to ensure more accurate and consistent sensory evaluations (Laves et al., 2022). The lack of these controls in our study represents a methodological limitation.

5. Conclusion

Our findings indicate that fNIRS can effectively capture significant neuronal activation patterns in response to different taste stimuli. Sweet and bitter tastes were found to elicit distinct activation patterns, with sweet tastes typically resulting in decreased neuronal activity and bitter tastes leading to increased neuronal activity. This aligns with existing literature on the neural correlates of taste perception and emotional responses.

Moreover, the study explored the relationship between basic taste sensitivity and hedonic preferences for food products. We observed that participants who recognized the basic tastes exhibited increased brain activity when tasting chocolates that matched these tastes, whereas those who did not recognize the basic tastes showed decreased activity. This suggests a link between taste sensitivity and hedonic responses, highlighting the potential of fNIRS to provide insights into individual differences in taste perception and preference.

Despite the small sample size, our regression analysis suggests that specific channels of neuronal activation correlate with overall liking of the chocolates, indicating the potential for fNIRS data to predict consumer preferences. However, further research with larger and more diverse samples is necessary to validate and refine these predictive models.

Ethics statement

This study was conducted in accordance with the ethical guidelines established for sensory evaluation and neuromarketing research. All participants were fully informed about the nature, purpose, and potential risks of the study before providing their consent. Written informed consent was obtained from all participants involved in the experiments. They were assured that their participation was voluntary and that they could withdraw from the study at any time without any consequences. Confidentiality and anonymity of the data were maintained throughout the study. The study was approved by the ethics committee of the HAW Hamburg Faculty of Life Sciences, under the process number 2020–09, titled "Discovering Consumer Preferences for Food Products using fNIRS". This approval confirms that the study complies with all relevant regulations and ethical guidelines.

CRediT authorship contribution statement

Stephan G.H. Meyerding: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Xiaochuan He:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Andrea Bauer:** Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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