



Comparing Taste Perception Across Modalities in Healthy Adults: Liquids Versus Dissolvable Taste Strips

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Abstract

Taste stimulation has rehabilitative value in dysphagia management, as it activates salient underlying afferent pathways to swallowing which may evoke feedforward effects on swallow biomechanics. Despite its potential beneficial effects on swallow physiology, taste stimulation's clinical application is limited for persons unsafe to orally consume food/liquid. This study aimed to create edible, dissolvable taste strips matched to flavor profiles previously used in research assessing taste's effects on swallowing physiology and brain activity, and to evaluate how similar their perceived intensity and hedonic, or palatability, ratings were between their liquid counterparts. Plain, sour, sweet–sour, lemon, and orange flavor profiles were custom-made in taste strips and liquid modalities. The generalized Labeled Magnitude Scale and hedonic generalized Labeled Magnitude Scale were used to assess intensity and palatability ratings for flavor profiles in each modality. Healthy participants were recruited and stratified across age and sex. Liquids were rated as more intense than taste strips; however, there was no difference in palatability ratings between the modalities. There were significant differences across flavor profiles in intensity and palatability ratings. Collapsed across liquid and taste strip modalities, pairwise comparisons revealed all flavored stimuli were rated as more intense than the plain profile, sour was perceived as more intense and less palatable than all other profiles, and orange was rated as more palatable than sour, lemon, and plain tastants. Taste strips have useful implications for dysphagia management, as they could offer safe and patient-preferred flavor profiles to potentially provide advantageous swallowing and neural hemodynamic responses.

Keywords Taste · Sensory perception · Neurotherapeutic

Introduction

Swallowing is a complex sensorimotor behavior of a semi-automated central pattern generator (CPG) response [1, 2]. When dysphagia occurs, sensory-, motor-, and/or sensorimotor-based deficits can make swallowing inefficient and unsafe. Despite the array of possible deficits, most methods to rehabilitate swallowing focus on motor versus sensory aspects of its physiology [3].

The standard approach for dysphagia treatment has included prescription of various strengthening exercises to

increase force-generating capacity and build endurance in oropharyngeal muscles [4]. A newer approach has emphasized skill-based training which incorporates motor learning principles to develop stable movement patterns through functional repetitions of the targeted task [5]. Although there is evidence to support the use of strength- and skill-based regimens to rehabilitate motor aspects of swallowing when applied with sufficient intensity to appropriate participants [6, 7], there are limited avenues in treatment to incorporate meaningful sensory experiences that could further assist recovery.

Sensation is a critical component for motor learning and re-learning of skilled movements [8–10], as perception is integral to refine and provide feedback on motor actions [11]. Sensory input is also integral in CPG responses, as it informs optimal timing and force parameters to specific movement sequences [12, 13]. Sensory stimulation could be of particular benefit in rehabilitating the swallow, as incoordination and mis-sequencing of swallowing movements can

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be key contributors to dysphagia [14]. Additionally, sensory stimulation of the oropharynx for persons who have dysphagia and are unable to safely eat by mouth could be immensely valuable during the rehabilitation process. People who are nil per os (NPO; i.e., unsafe to consume an oral diet) are subject to prolonged periods of minimal oral stimulation. Neural underpinnings of sensorimotor behaviors that are inactive for long durations are susceptible to weakened sensory processing and motor control from disuse or deconditioning effects [15], an effect commonly known as the neuroplasticity principle of “use it or lose it” [16]. A sensation that could be of potential benefit to incorporate in swallowing rehabilitation is taste, as it involves numerous overlapping neural pathways and substrates with swallowing [17, 18].

The processing of taste begins with chemoreceptors within taste buds. Taste receptor cells within taste buds interact with tastants, and gustatory information is mediated via the facial, glossopharyngeal, and vagus cranial nerves to the key sensory nucleus of the swallowing CPG in the medulla, the nucleus tractus solitarius [NTS; 19]. Taste information is then relayed by the thalamus to the gustatory cortices which include the insula, frontal operculum, and orbitofrontal cortex [20]. The neural processing of taste also coincides with other brain areas associated with oropharyngeal sensorimotor function, since taste is a multisensory experience that interacts with olfaction and oral somatosensation [21].

Many factors can modulate gustatory experiences, as taste can be affected by age [22], salivary production [23], satiety [24], and cognitive processes like attention and memory [25]. Genetic taste status (GTS) also contributes to taste processing, which refers to people’s inherent differing levels of sensitivity to taste [26]. GTS can be determined using the chemical compound PROP [6-n-propylthiouracil]. People’s perceptual intensity rating of PROP is used to categorize them as non-tasters, mid-tasters, or super-tasters [27, 28]. Differences in taste-related anatomy and perception have been observed across GTS groups, as super-tasters have a higher density of taste buds on the anterior tongue and perceive more intense responses to taste stimuli than mid- and non-tasters [29, 30]. In consideration of the multitude of factors that influence taste, its assessment can be a complex and variable process. Taste can be assessed via psychophysical scales that measure intensity and/or palatability attributes of a tastant [31] or threshold procedures to detect, recognize, and/or distinguish tastes [32]. Tests of taste stimulation can be administered focally on the tongue or via the whole-mouth [33]. Taste is becoming an increasingly relevant variable of interest to quality of life [34] and clinical management of swallowing disorders [35, 36].

Taste is posited to have a feed-forward effect on swallowing movements, as greater sensory input may elicit more efficient motor responses in CPG-mediated behaviors

[13, 37]. Beneficial effects of taste stimuli on swallowing physiology have been observed in healthy populations and persons with dysphagia, and these effects have included faster and greater/stronger movements in swallowing biomechanics [38–42]. Common taste profiles used to investigate taste’s effect on swallowing which have reported an advantageous effect in comparison to other tastants have included sour [30, 38, 41, 43, 44], sweet [41, 45], sweet–sour [38, 46], and lemon-flavored [39, 42, 47] stimuli. The influence of taste stimulation on swallowing could be related to taste’s reported effect of increased activation in neural structures fundamental to swallowing [48, 49].

Although taste’s potential therapeutic effects of increased neural activation and improvements to swallowing physiology could possibly assist recovery from swallowing disorders, its clinical application can be challenging. Since a majority of the research on taste has investigated its effects using liquid boluses, the potential therapeutic benefits aren’t applicable to people who are NPO. Taste stimulation that avoids the risk of airway compromise could be an invaluable clinical tool to supplement rehabilitation. A possible method to provide taste stimulation safely to persons with dysphagia could be in the form of dissolvable taste strips. Dietsch et al. [50] employed taste strips with real food flavors to persons with and without dysphagia and/or xerostomia. The taste strips were associated with moderately increased salivary production and highly preferred hedonic ratings by both groups, but no indications of difficulty managing the increased secretions by any participants. Despite their high palatability and beneficial results on production of saliva, the taste strips used in Dietsch et al. [50] do not match the taste profiles that have been associated with positive effects on swallowing physiology and neural activity. For taste strips to be implemented clinically in persons with dysphagia, it is critical to ensure that the strips can provide a similar type and level of stimulation of the flavor profiles documented in the literature to extrapolate their potential effects on swallowing and brain activity.

The aims of the current study were to compare taste-related ratings of intensity and palatability between liquid and taste strip modalities of flavored stimuli, and to assess any perceptual differences in intensity and palatability ratings across flavor profiles. The taste strips made in this study were designed to specifically match the flavor profiles of the liquid tastants that have been used in other studies investigating swallowing biomechanics and neural hemodynamics in response to taste stimuli [17, 35]. It was hypothesized that intensity and palatability ratings would be similar for liquid tastants and taste strips across flavor profiles (H1), and intensity and hedonic ratings would differ from one flavor profile to another within liquid and taste strip modalities (H2).

Methods

Participants

Healthy adult volunteers were recruited for study participation from two age groups. Due to the absence of relevant comparable studies to guide effect size estimates, we were unable to complete a power analysis and instead simply maximized recruitment efforts within the study timeline. The younger age group ($N = 17$ total) consisted of participants from 19–33 years of age, and the older group ($N = 15$ total) was comprised of adults 55 years of age and older. All participants provided informed consent and completed a brief medical history questionnaire. Participants were excluded if they had any taste, smell, speech, swallowing, or neurologic disorders. All food-related allergies were reported to ensure safe consumption of taste trials. The global pandemic of COVID-19 occurred during data collection of this study, and any participants enrolled following the pandemic completed a COVID-19 safety screening form following the Center for Disease and Control guidelines. If participants marked any symptoms or known exposures of COVID-19, they were excluded from participation. Only one participant had reported to previously test positive for COVID-19; however, the participant had COVID-19 over a month prior to research participation and reported no initial or continuing disturbances with taste and smell perception so was included in the study. The study protocol was approved by the relevant Institutional Review Board (#17711).

Stimuli

Liquids

Five custom-made liquid tastants were prepared in distilled water. Liquid taste stimuli included (a) intense sour, (b) sweet–sour, (c) lemon, (d) orange, and (e) unflavored. These specific liquid formulations have previously been used in a range of experiments assessing the effect of taste stimulation on brain activity and swallowing physiology in healthy and

dysphagic adults [35, 38, 51, 52]. All liquid stimuli were classified as Level 0 thin liquid via the flow test method and criteria of the International Dysphagia Diet Standardization Initiative [53] and were clear-colored. Flavored liquid stimuli are described in Table 1.

Taste Strips

Edible and dissolvable taste strips were designed in five custom-made flavors: (a) intense sour, (b) sweet–sour, (c) lemon, (d) orange, and (e) plain/unflavored. The objective was to match the features of the liquid stimuli that have already been shown to beneficially influence neural activity in swallowing-related areas as well as swallowing physiology, so the taste strips can eventually be used to provide taste stimulation for persons with dysphagia who are unable to safely tolerate the liquid stimuli. For each taste profile, taste strip ingredients including citric acid, sweetener, food-grade polymers listed on the FDA GRAS list, and flavored extract (as relevant for each tastant type) were combined in distilled water using precise measures and sequences with different temperatures at each stage. The resulting solutions were then spread on 1/16" thick polyethylene terephthalate glycol sheets (McMaster-Carr, Chicago IL), and dried completely in a food dehydrator (Biochef, Salt Lake City UT). The dried tastant sheets were subsequently cut into 25 mm × 30 mm rectangles; this size was determined based on both the typical size/shape of an adult's tongue blade (for maximum coverage) and the total dosage of tastant per strip that these proportions would yield. Each type of taste strip was stored in a separate airtight container labeled with batch information. All flavors of taste strips were paper-thin and clear-colored.

Whereas the ingredients, proportions, and doses for the liquid stimuli are well-established [35, 38, 51, 52], the taste strips were newly developed. Data collection was initiated using taste strips that were based on similar proportions of the flavor-related ingredients as the liquids and had subsequently undergone multiple rounds of internal testing and refinement to approximate the targeted texture and taste features. In response to preliminary results from the first

Table 1 Recipes for liquid tastant stimuli; distilled water was used for the plain liquid tastant and as the solvent for all other stimuli

Tastant	Citric acid	Sucrose	Lemon extract	Orange extract
Sour	2.7% wt/vol	N/A	N/A	N/A
Sweet–Sour	1.11% wt/vol	8% wt/vol	N/A	N/A
Lemon	1.11% wt/vol	8% wt/vol	1% vol/vol	N/A
Orange	1.11% wt/vol	8% wt/vol	N/A	1% vol/vol
Source	Fisher scientific citric acid USP	C&H granulated pure cane sugar	McCormick pure lemon extract	McCormick pure orange extract

Wt/vol weight to volume, *vol/vol* volume to volume

17 participants, the taste strip recipes were further revised. The goals of the additional modifications were to (a) reduce stickiness and brittleness of the strips, and (b) increase the intensity of tastants. The revisions to the taste strip recipes included adjusting the polymer amounts, increasing the citric acid by 50–67% (depending on taste profile), replacing the original sweetening agent with another (where applicable), and reducing the amount of flavor extract (where applicable). Only the data from the revised recipes were included in the analyses reported here to address the research hypotheses.

Procedures

Prior to administration of any taste trials, researchers collected information about what participants had last consumed and when, to ensure that participants had not ingested anything for at least an hour prior to testing. Participants rinsed their mouth with distilled water before each stimulus trial.

The order of stimulus presentation was counterbalanced by modality, such that a participant either completed all liquid trials prior to any taste strip trials, or all taste strip trials before any liquid ones. Within each modality, seven trials (one of each of the five flavor profiles plus repeated trials of two flavors selected at random) were administered in a random order. This resulted in a total of 14 trials per participant. All taste trials were self-administered by the participants, who were blinded to the flavor profiles of tastants. The taste strips were presented in 25 mm X 30 mm rectangles and the liquids were in 5 ml quantities in disposable paper cups. All taste strip and liquid stimuli were visually indiscernible from each other and were administered at room temperature. Researchers followed a verbal script in educating participants on the perceptual rating scales, instructing them how to accurately and reliably use the scales, and confirming comprehension [54, 55]. After each taste trial, participants were instructed to immediately complete taste intensity and palatability ratings using printed copies of the generalized Labeled Magnitude Scale (gLMS; 54; Fig. 1) and hedonic generalized Labeled Magnitude Scale (HgLMS; 55; Fig. 2), respectively. For each trial, the participants made a mark bisecting the vertical line at whatever point matched their perception of taste intensity (for the gLMS ratings) or pleasantness (for the HgLMS ratings). Before participants tried the next stimuli, they were instructed to rinse their mouths with room-temperature distilled water until they could no longer detect the previous taste stimulus.

Following the last taste trial, GTS was determined using a dissolvable film impregnated with PROP (Sigma-Aldrich; 28). Participants were told that taste is influenced by genetics, and that determination of their GTS will assist in the analysis and interpretation of the data. Participants self-administered the PROP strip on the blade of their tongue

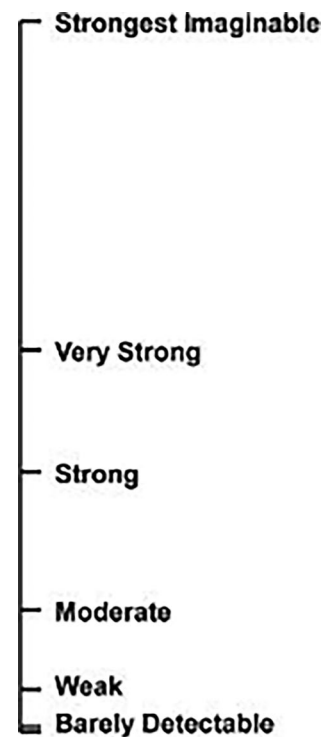


Fig. 1 The generalized labeled magnitude scale (gLMS) was used to rate intensity for taste strip and liquid stimuli. Possible scores range from 0 (undetectable) to 100 (strongest sensory experience imaginable)

and were instructed to let it dissolve. They then rated the intensity of any perceived taste using the gLMS as described above. During analysis, these PROP ratings were used to classify their taste status group (i.e., super-, mid-, or non-taster; 28).

Analysis

Ratings were extracted from the data collection sheets by measuring the distance from the zero point at the bottom (for gLMS) or center (for HgLMS) of the vertical line to the participant's mark for each trial and scale, as well as the actual length of each line. These values were converted to gLMS ratings from 0 (undetectable) to 100 (strongest sensory experience imaginable), and HgLMS ratings from – 100 (most disliked sensation imaginable) to 100 (most liked sensation imaginable). Only the taste strip ratings based on the revised recipes were included in the analyses reported here.

To address H1, one-way analyses of variance (ANOVA) were performed to examine the difference between ratings of taste strips created using the revised recipe versus liquid stimuli on outcome variables of intensity and palatability. To address H2, additional one-way ANOVAs were completed to investigate mean differences in intensity and palatability ratings by taste profiles (collapsed across taste strips and

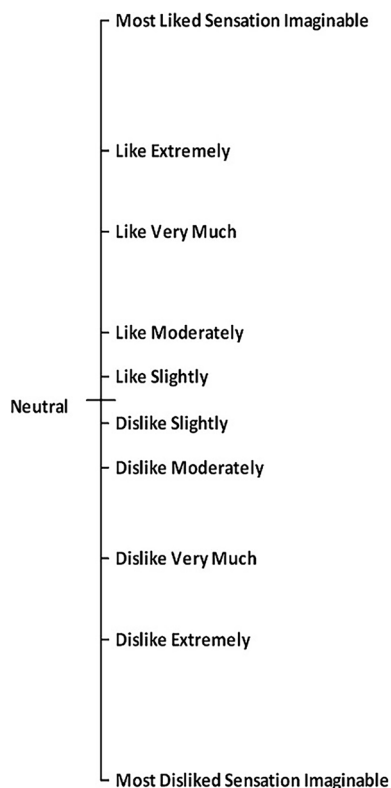


Fig. 2 The hedonic generalized labeled magnitude scale (HgLMS) was used to rate hedonics for taste strip and liquid stimuli. Possible scores range from -100 (most disliked sensation imaginable) to 100 (most liked sensation imaginable)

liquids). Significant alpha levels were set at 0.05 for ANOVAs, and post-hoc testing of intensity and palatability ratings across taste profiles were set at a Bonferroni-adjusted 0.01 for alpha level significance.

A univariate between-groups factorial ANOVA was performed to examine if participant’s sex, age group, or GTS had any main or interactional effect on intensity and/or palatability ratings.

Results

Participants

A total of 32 healthy adults participated in the study. Ongoing efforts toward age- and sex-balancing of participants yielded 17 persons in the younger age group (mean age = 24.59 years, range of 21–31 years, nine women), and 15 persons in the older age group (mean age = 67.2 years, range of 55–84 years, eight women) with proportional distribution across the original and revised sets of recipes. GTS distribution among this cohort included 12 non-tasters, eight mid-tasters, and 12 super-tasters. Participant demographics for the data associated with each batch of taste strip recipes are shown in Table 2.

Results of univariate between-groups factorial ANOVA included no significant main or interactional effects for participant variables of age group, sex, or GTS on gLMS or HgLMS ratings.

H1:Modality (Taste Strips vs. Liquids) on gLMS and HgLMS

Contrary to H1, there was a statistically significant difference in intensity (gLMS) ratings between the revised taste strip recipe and liquid tastants, $F [1, 201] = 5.13, MSE = 2212.31, p = 0.025$. (Of note, this strip-liquid difference was less extreme than the preliminary results obtained with the original strip recipes, $F [1, 236] = 12.10, MSE = 5708.75, p < 0.001$). Collapsed across taste profiles, liquid tastants ($M = 35.11, SD = 22.41$) were rated as more intense than the revised-recipe taste strips ($M = 28.51, SD = 18.84$) stimuli. Average intensity ratings among taste profiles across liquid and taste strip modalities from the revised recipes are presented in Fig. 3.

In support of H1, there was not a significant difference in palatability (HgLMS) ratings between the revised taste strip recipe and liquid tastants $F [1, 201], = 1.59, MSE = 1004.251, p = 0.209$. Liquid ($M = 6.51, SD = 25.89$)

Table 2 Participant demographics organized by sex, age, and genetic taster status across the original and revised taste strip recipes

Taster status group	Original recipes				Revised recipes			
	Non	Mid	Super	Total	Non	Mid	Super	Total
Men								
Older	1	0	2	3	4	0	0	4
Younger	2	1	2	5	2	1	0	3
Women								
Older	1	0	3	4	1	2	1	4
Younger	2	2	1	5	0	1	3	4
Total	6	3	8	17	7	4	4	15

Taste perception data associated with the original recipes informed recipe modifications. Data associated with the revised recipes was included in the hypothesis testing reported here

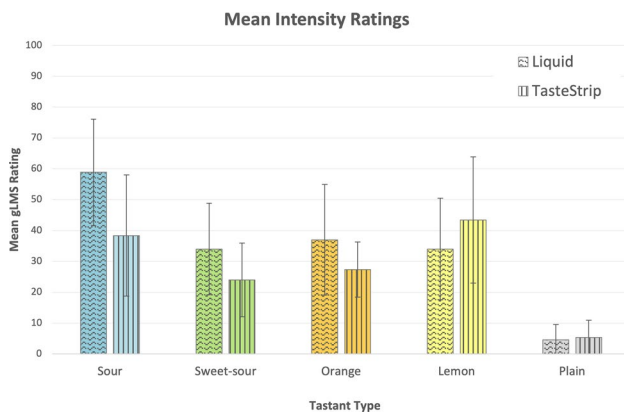


Fig. 3 Average generalized labeled magnitude scale (gLMS) ratings for flavor profiles across liquid and taste strip modalities

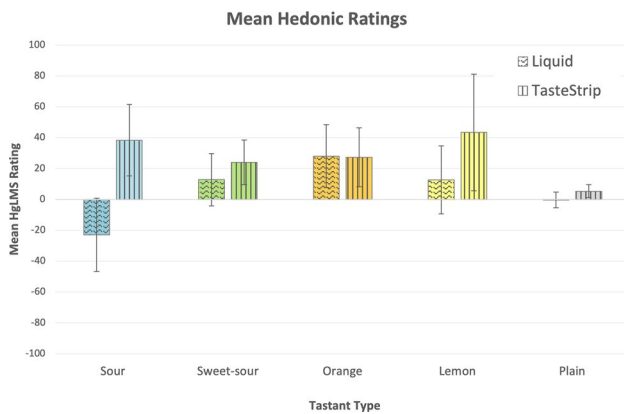


Fig. 4 Average hedonic generalized labeled magnitude scale (HgLMS) ratings for flavor profiles across liquid and taste strip modalities

and taste strip ($M = 2.06$, $SD = 24.29$) stimuli were rated similarly in how well they were liked or disliked. Average palatability ratings among taste profiles across liquid and taste strip modalities from the revised recipes are shown in Fig. 4.

H2:Taste Profiles on gLMS and HgLMS

In support of the research hypothesis (H2), there were significant differences in intensity (gLMS) ratings across taste profiles, $F [4, 198] = 38.15$, $MSE = 9671.94$, $p < 0.001$. Collapsing taste profiles across modalities, pairwise comparisons using Bonferroni-adjusted alpha levels of 0.01 revealed that sour stimuli were rated as significantly more intense than sweet-sour, orange, lemon and unflavored profiles. All

flavored stimuli were rated as significantly greater in intensity than the unflavored stimuli.

Sour ($M = 58.86$, $SD = 17.22$) was rated as most intense of the liquid stimuli overall, whereas orange ($M = 37.02$, $SD = 17.92$), lemon ($M = 34.03$, $SD = 16.45$), and sweet-sour ($M = 34.02$, $SD = 14.81$) profiles had similar intensity ratings. Lemon ($M = 43.45$, $SD = 20.44$) was rated as the most intense profile for taste strips followed by sour ($M = 38.40$, $SD = 19.60$), whereas orange ($M = 27.35$, $SD = 8.95$) and sweet-sour ($M = 24.03$, $SD = 11.97$) were reasonably comparable to another.

Also consistent with the research hypothesis (H2), there were significant differences in palatability (HgLMS) ratings among taste profiles, $F [4, 181] = 13.31$, $MSE = 5774.90$, $p < 0.001$. Pairwise comparisons of taste profiles collapsed across liquids and taste strips using Bonferroni-adjusted alpha levels of 0.01 revealed that sour was rated as significantly lower in palatability ratings than sweet-sour, orange, and lemon taste profiles. In other words, participants disliked the sour stimuli in comparison to other tastants. Orange flavored stimuli were most preferred among participants and had significantly higher palatability ratings than sour, lemon, and plain tastants.

Sour had the lowest palatability ratings in liquid ($M = -22.91$, $SD = 23.80$) and taste strip ($M = -5.45$, $SD = 23.22$) modalities. Sweet-sour liquid ($M = 12.79$, $SD = 10.92$) and taste strips ($M = 5.15$, $SD = 14.48$) had positive averages in the hedonic scaling, and orange had the highest average palatability rating (liquid: $M = 28.07$, $SD = 20.33$, taste strip: $M = 14.59$, $SD = 19.10$), indicating participants liked the taste of these profiles. Interestingly, lemon liquid ($M = 12.69$, $SD = 21.99$) was rated as pleasant but the lemon taste strips were rated as unpleasant ($M = -7.45$, $SD = 37.82$) to participants.

Notably, the ratings for lemon taste strips were skewed by two outliers. Two participants associated that stimulus with cold medicine; their palatability ratings (i.e., $-75/100$ and $-64/100$) were quite low compared to those of all other participants whereas their intensity ratings for the lemon taste strips were substantially higher than others'. When these outliers were temporarily removed from analysis, the ANOVA results remained statistically significant but descriptive statistics shifted slightly; the revised recipe lemon taste strips ($M = 39.15$, $SD = 15.72$) were more similar to sour ($M = 38.40$, $SD = 19.60$) in intensity ratings and the hedonic scores bumped from a mean of -7.45 ($SD = 37.82$) to -1.26 ($SD = 33.68$) when the two outliers were excluded. Ultimately, these datapoints were retained in the analyses of variance to reflect the many factors that can modulate gustatory experiences which are inherently related to taste perception [36].

Discussion

The aims of the study were to investigate if ratings of taste intensity and palatability were similar between liquid taste stimuli and novel taste strips developed in our lab, and to examine any differences in perceived intensity and enjoyment across taste profiles. The study's results include a statistically significant difference between intensity ratings of liquids and taste strips, but no meaningful difference in ratings of palatability between the two modalities. Participants perceived liquid tastants as more intense than taste strips, but rated each modality similarly in how well they were liked or disliked. There were significant differences among average ratings of intensity and palatability between taste profiles. For intensity ratings, participants rated all flavored stimuli as more intense than the unflavored stimulus, and sour was rated as the most intense stimulus. Participants perceived sour as the least preferred and orange as the most preferred tastant.

The disparity in intensity measurements between liquid and taste strip stimuli could be attributed to differences of ingredient concentrations in the taste stimuli modalities and partially inherent to how each stimulus modality interacts with the oral cavity. Liquid trials typically flow throughout the oral cavity and provide a whole-mouth sensory experience, whereas taste strips dissolve in place and provide a more focal/regional taste experience. Whole-mouth taste administration stimulates almost all oral taste buds [32], which would elicit sensory impulses from a notably greater number of taste receptor cells compared to regional taste testing. Perhaps the concept of super-tasters having a genetically higher density of taste buds and perceiving tastes at a heightened intensity in comparison to mid- and non-tasters who have a lower taste bud density [29, 30, 56] may be relevant, as more taste bud stimulation could correlate to a higher perceived taste intensity. Additionally, the liquid stimuli have greater potential for chemesthetic stimulation to the trigeminal pathway than would the smaller-portioned, thin taste strips. The liquid stimuli may provide more pressure and somatosensation to the oral cavity which functionally overlaps with taste processing pathways [57]. Recent evidence also suggests regional intensity differences across the tongue. Higgins and Hayes [58] reported that participants perceived different intensity levels of bitter stimuli at different loci of the oral cavity and gustatory papillae. Variations of taste intensity across lingual regions could potentially be an important factor to differences in intensity ratings between whole-mouth versus regional taste stimulation.

Palatability ratings were comparable between the revised recipe of taste strips and liquids, as participants had similar likings or dis-likings of the tastes across

modalities. This is promising in terms of translating previously-tested liquid tastants to a form that is safer for individuals with dysphagia, because it can provide a more accurate generalization of results on the effects the taste strips may offer on swallowing biomechanics and neural activity. An interesting point to consider in regards to palatability ratings is that participants were blinded to the taste profiles of stimuli which may have affected the ratings, as cognitive and psychological processes like expectation can influence taste experiences and perception [59]. For example, someone who received an orange-flavored stimulus on the first trial followed by a sour stimulus might have rated the second trial more negatively due to a more dramatic dissonance between expectation (e.g., expecting pleasant and familiar fruity flavors) and experience (i.e., receiving an intense sour taste). Hedonic scores may have been improved or more stable if participants had an accurate reference or expectation of the taste experience, as would be the case in clinical utilization of taste strips during dysphagia rehabilitation (when experimental controls are less relevant).

Most taste profiles had positive average palatability ratings, meaning participants enjoyed the taste stimulation to a certain degree. Profiles that had average negative palatability ratings included sour for both modalities and lemon-flavored taste strips. Interestingly, a large portion of studies investigating taste's effect on swallowing have used sour as a pure taste contrast and lemon-flavored stimuli as a complex-taste contrast [36]. If taste stimulation is to be used as a compensatory or rehabilitative tool in management of dysphagia, it would be ideal if people could have options of tastants that have been linked to neurological/physiological benefits *and* were individually palatable for them. Enjoyable taste experiences in which people can choose their own tastants fits well within the "patient preferences" aspect of the evidence-based practice framework [60] and could facilitate adherence to recommendations, which is a known challenge in dysphagia management [61].

The custom-made taste strips could have meaningful clinical applicability for the management of dysphagia. In our previous work within this research line, liquid barium trials of the sour and sweet-sour profiles were associated with less instances of airway invasion and greater magnitudes of movement in swallowing morphometry compared with swallows of plain barium stimuli in persons with confirmed sensory-based dysphagia [38]. The liquid profiles used in this study, which the taste strips were deliberately designed to match, have also been used to investigate taste's effect on neural activity using functional magnetic resonance imaging. Compared to a neutral stimulus (i.e., water), tastants led to significant blood-oxygen-level-dependent changes in the pre- and post-central gyri, insula, anterior cingulate cortex, and secondary/associative sensorimotor areas in healthy

young participants [17]. These neural areas are primary cortical and sub-cortical regions active in swallowing [18]. The increased blood flow from taste stimulation provides the swallowing neural network with greater metabolic support for function. This process is known as functional hyperemia [62], which is a favorable condition to elicit neuroplasticity.

The use of sensory input to facilitate adaptive functional neuroplasticity and sensorimotor function, which are primary goals for incorporating taste stimulation into dysphagia rehabilitation, has been well-established using other modalities. For example, repetitive sensory stimulation (RSS) has been associated with rapid increases of blood flow to sensorimotor brain areas [63]. Further, RSS has been reported to quickly evoke structural and functional neuroplasticity in sensory networks [64, 65], and to increase accuracy of skilled movements when applied prior to task performance [66]. Since taste profiles in this study have been observed to provide immediate effects in swallowing biomechanics and neural hemodynamic responses in overlapping neural substrates of the swallowing network, this taste stimulation might serve as an effective primer for improved swallowing biomechanics and a potential vehicle to evoke adaptive functional neuroplasticity in the swallowing network. Sensorimotor priming from safe taste stimulation could be used as an adjunct with motor-based treatment regimens to elicit more accurate and reliable movement patterns during swallow training, and with sufficient intensity, specificity, and feedback, rehabilitation experiences are optimized to facilitate neuroplasticity and sustained skill improvements [12, 16, 67].

Taste strips could also be of particular significance to prevent exacerbation of dysphagia and facilitate rehabilitation for persons who are NPO. Persons with dysphagia have been observed to swallow less frequently than those without dysphagia in the acute stroke population [68], and an NPO status could burgeon this effect. Chronic disuse of muscles, like oropharyngeal muscles from not eating or drinking anything by mouth, could lead to muscular atrophy [69] and central maladaptation from insufficient activation of neural pathways [70]. Taste strips could be a safe modality to receive taste stimulation and combat these issues for persons who are NPO. The commercially-produced taste strips previously employed by Dietsch et al. [50] led to increased production of saliva which was tolerated even by people with significant dysphagia on an altered diet or with an NPO status. Perhaps taste strip stimulation could provide persons unsafe to eat/drink anything by mouth a combined effect of salient neural stimulation and increases in salivary production, which could lead to a higher amount of spontaneous swallows. These effects could prevent further deconditioning in strength and skill function and impairment in sensorimotor processing and control. Taste strips may also be a valuable tool during

critical periods of recovery from brain damage (i.e., stroke, traumatic brain injury) to possibly guide recovery of specific and salient neural circuits in swallowing via taste strip stimulation and prevent maladaptive patterns of neuroplastic compensation [71].

As with all research, this study has limitations. The nature of pioneering the taste stimuli with progressive validity checks and recipe revisions reduced the number of trials associated with the final recipes for each taste profile, and therefore affected sample size and statistical power for the final analysis presented here. Additionally, there are multiple challenges inherent to taste research. Although dependent variables of the gLMS and HgLMS are validated assessments of perceptual intensity and hedonics [54, 55], they are subjective scales measuring a sensation that can be modulated by a multitude of factors which all could affect measurement validity. Another limitation is that the taste strips used in the study are being custom-made by the authors for research purposes and are not currently commercially available, and additional steps are necessary before they can be implemented clinically and in broader populations.

In conclusion, custom-made taste strips matching flavor profiles used as stimuli in swallowing and neuroimaging studies were designed to assess their perceptual differences with liquid counterparts. Taste strips were perceived as less intense than liquid tastants; however, both modalities were similarly rated in how pleasant or unpleasant they were perceived. These custom-made taste strips have valuable clinical implications for dysphagia management, as they can provide safe and salient sensory stimulation to potentially facilitate improved swallow physiology and optimal neural reorganization in persons with dysphagia following neurologic injury. Future directions in this research line include continued validation of intensity and hedonic measurements of taste strips in larger sample sizes and investigations of taste strips' effects on swallowing physiology and neural activity in healthy and clinical populations. Progress in these next steps will elucidate taste strips' clinical relevance and rehabilitative potential for persons with dysphagia.

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Data Availability The de-identified raw data supporting the conclusion of the manuscript will be made available by the authors upon reasonable request.

Declarations

Conflict of interest None of the authors have financial conflicts of interest to disclose. Dr. Dietsch holds a provisional patent on the dissolvable flavor films used in this study.

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