Predicting subjective liking of bitter and sweet liquid solutions using facial electromyography during emptying, swirling, and while thinking about the taste.

Short Title: Predicting liking of liquid solutions using electromyography

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Abstract

Hedonic responses to foods are often measured using subjective liking ratings scales. This is problematic because food behaviours are complex and single measurements points that occur after tasting are unable to capture an individual's dynamic affective state. To address this limitation, techniques have been developed to sample subjective affective responses during oral processing, such as temporal dominance of emotion. These methods are also limited because they interrupt natural behaviours associated with food and oral processing. The present research investigates the potential use of electromyography as a means to predict subjective liking ratings using affective facial muscle activity recorded at different phases of oral processing while tasting liquids. Using linear mixed models, muscle activity recorded while emptying into the mouth, swirling, and thinking about the taste of bitter and sweet liquid solutions was used to predict subjective liking ratings. During different phases of the tasting, these mixed models demonstrate that zygomaticus major activity predicted increased liking and that corrugator supercilii and levator labii superioris predicted decreased liking. The change in liking ratings predicted by each muscle varied depending on whether participants were emptying, swirling, or thinking about the taste. We conclude that facial muscle activity is a valuable measure of affective responses during dynamic food behaviours.

Keywords: Liking; Food; Liquid; Electromyography; Affect.

Ethics statement

The research was reviewed by Massey University Human Ethics Committee: Northern (Approval No. MUHECN 14/040)

Introduction

Hedonic responses to food taste and texture can result in changes to an individual's affective state and are important in determining subjective liking judgments and preferences. But most investigations of hedonic responses to foods rely on sampling subjective measures rather than directly assessing an individual's affective state.

Subjective responses to foods are usually measured by presenting individuals with visual analogue scales, Likert scales, or categorical scales after oral processing is completed [1,2]. Although these techniques provide valuable data on subjective responses to food, they are limited because they sample affective responses at a static point in time. Food behaviours are dynamic and affective responses to food might vary during eating because the interplay between food properties, oral processing, and sensory responses are dependent on physical and physiological phenomena such as mastication or salivation [3].

One solution for the difficulties associated with assessing food liking with static measures, is to use dynamic measurement techniques to provide continuous subjective measurements across the timecourse of oral processing [4-7]. Although methods that continuously sample participants' subjective judgments have provided valuable insights for liquids and solid foods [8-11], there are some problems with these techniques. The main drawback of sampling subjective responses during food behaviours is that the process of asking participants to rate their hedonic liking interrupts normal behaviour and might change this behaviour. In addition, subjective ratings do not always provide an accurate measure of an individual's true affective state and might be biased by social desirability concerns [12].

The present study uses psychophysiological measurement, facial electromyography (EMG), to quantify affective responses to foods by recording facial muscle activity associated with emotional facial expressions. To our knowledge, the earliest research investigating the

relationship between facial expressions and taste and odour stimuli found that for new-borns unpleasant stimuli evoked disgust responses and pleasant stimuli evoked positive emotion expressions such as smiles [13]. Gilbert et al. [14] found similar results using facial action coding with adult participants who made posed or real facial expressions in response to odours, although they found that it was more difficult to capture and identify positive facial responses to pleasant foods. Unfortunately, weak affective responses relating to low intensity hedonic experiences might not result in visible displays of facial emotion and these subtle facial expressions are difficult to detect using video based methods and behaviour observation [15]. An alternative is to measure affective facial responses using electromyography (EMG) to quantify muscle activity relating to facial expressions of emotion. Muscles corrugator supercilii, levator labii superioris, and zygomaticus major are commonly used in studies that detect affective states related to hedonic experiences [16-19]. Contractions of these muscles result in movement of the skin to form emotional facial expressions. Corrugator, located under the brow region, furrows and knits the brow in situations that evoke negative affect and when encountering unpleasant stimuli [20,21]. The levator muscles act to lift the middle of the upper lip and wrinkle the nose in negative affective states, but maximally to those evoking disgust [17,19]. Zygomaticus raises the corners of the mouth in smile facial expressions and its activity tends to increase during exposure to positive stimuli or when experiencing positive mood [17,22-24].

The use of facial EMG to quantify the relationship between taste or odour stimuli and hedonic experiences has been demonstrated several times, but there have been limitations to these previous studies. Jancke and Kaufmann [25] investigated facial EMG responses to odour in solitude and with an audience by measuring six muscle regions (M. corrugator supercilii, M. procerus, M. nasalis, M. levator, M. orbicularis oculi and M. zygomaticus major). They found mixed results depending on whether their participants were exposed to

odourants in private or with an audience: negative affective facial muscle activity was evoked by aversive odours regardless of the social setting, but pleasant odours only evoked positive facial muscle activity with an audience; critically, they found no correlation between valence ratings and facial muscle activity. Levator muscles have also been demonstrated to discriminate flavours such as apple juice from soy milk and pickle juice [26], although within this previous study there was no analysis of the relationship between ratings and muscle activity beyond that a statistically significant mean difference between samples could be detected. Encouragingly, Horio [27] investigated hedonic responses to sweet, salty, sour, bitter, and umami using EMG activity (frontalis, corrugator, orbicularis, masseter, risorius, orbicularis, depressor anguli, and digastricus) and found that there was a linear relationship between muscle activity and subjective ratings for some muscles; unfortunately these analyses relied on correlations and did not attempt to explain the unique contribution of each muscle whilst controlling for activity of other muscles. In addition, these correlation analyses do not provide sufficient information to determine if the analyses used a traditional approach with subject as the unit of analysis or an item analysis approach.

In summary, there have been a few studies that have successfully used facial EMG to discriminate hedonic liking for food relevant stimuli. But there have been mixed results when attempting to correlate subjective responses with facial muscle activity. The present study builds upon these previous findings by using a mixed model approach to explain the unique contribution of facial muscles relevant to emotion for predicting subjective liking judgments based on hedonic responses to bitter and sweet solutions at different stages of oral processing of liquids.

Based on previous findings, the present study had three hypotheses. H_1 : facial muscle activity would predict subjective liking ratings, with increased corrugator and levator activity associated with decreased liking and increased zygomaticus activity associated with increased

liking; H₂: the relationship between facial affect and liking would be present throughout the different stages of liquid tasting (emptying into the mouth, swirling, thinking about the taste); and H₃: the relationship between facial affect and liking would be present when tasting only (muscle activity predicting liking ratings in a later rating block) and when tasting and rating (within the same block).

Methods

Participants

Twenty medium tasters aged from 20-40 years (half female) participated and had a mean age of 27 years. All participants had previously attended a screening session to assess PROP taster status and were selected to participate in the current study because they were medium PROP tasters. One participant's data was excluded from all analyses because their facial EMG activity was consistent with yawning throughout the experiment. Potential participants were screened to exclude those who smoked, reported current or past oral or nasal diseases, were pregnant and were taking medication that influenced taste and odour sensitivity. The research was approved by Massey University Human Ethics Committee: Northern (Approval No. MUHECN 14/040). Informed consent was gained and participants were debriefed after completion of the final recording session and were given a NZ\$20 gift card after participation.

Stimuli

Sweet liquid solutions were produced using food grade white sugar (Chelsea, New Zealand) and bitter solutions were produced using analytical quinine hydrochloride (bitter; Sensient Technology, New Zealand). Sweet taste stimuli were solutions of reverse osmosis (RO) water containing 0.09M, 0.36M and 1.14M sucrose, and bitter stimuli were solutions of RO water containing 5.0×10^{-7} M, 5.0×10^{-4} M and 5.0×10^{-3} M quinine. Solution concentrations

were chosen from a wider range of concentrations tasted and rated by a different group of medium PROP taster participants. The final solution concentrations were selected because they could be discriminated using a labelled affective magnitude scale (LAM) and labelled magnitude scale (LMS) and did not result in a long lasting aftertaste.

Procedure

At each physiological testing session, participants were required to wash their face using a facial cleanser (Cetaphil, Johnson & Johnson); electrode sites were then prepared using isopropyl alcohol swabs and electrode gel (Signagel, Parker Laboratories) to reduce impedance. EMG electrodes were attached and the participant was seated in a testing booth to relax while their EMG recordings settled.

Bitter and sweet tasting sessions were scheduled on different days and each was composed of three blocks: training, tasting only, and tasting with rating. For the training block, a RO water sample was served so that participants could become familiar with the tasting trial instructions. In the tasting only block, participants tasted all of the liquid samples in a random order while their facial EMG activity was recorded. The tasting and rating block was identical to the tasting block with the additional requirement that participants provided subjective liking and intensity ratings for each of the liquid samples using the affect (LAM) and intensity (LMS) scales. During the tasting and tasting and rating blocks, three concentrations (low, medium, and high) of the bitter or sweet solutions and water control were each replicated three times in a random order. Sweet and bitter testing sessions were conducted on different testing days.

Instructions were presented to participants using E-prime 2 [28] to minimise contact with the experimenter. In the *tasting only block*, for each solution the participant was instructed to pick up and hold the sample cup and prepare to empty the liquid into their mouth. Then the

emptying phase screen instructed the participant to empty the liquid sample into their mouth and click the mouse button. Immediately following the mouse click, the *swirling phase* screen instructed participants to swirl the liquid in their mouth for 5 seconds. After swirling, an instruction was given to spit out the solution and click the mouse button. After spitting, the *thinking phase* screen instructed the participant to think about the taste of the liquid for 10 seconds. Finally, participants rinsed their mouth twice with water (or until the aftertaste had been removed) and were then asked to take a 5-second break before next trial started. The *tasting and rating block* was identical except that two rating scales were presented after the thinking screen but before rinsing the mouth. For the statistical analyses these are referred to as: emptying phase, swirling phase, and thinking phase.

Facial electromyography

Muscle activity was recorded using a BIOPAC MP150 physiological recording device (BIOPAC Systems Inc., Goleta, CA) and three EMG100C amplifiers, with silver/silver chloride reusable surface electrodes (4mm in diameter). The raw EMG signal from each facial muscle was amplified by 1000x and then hardware filtered with a high pass 10 Hz and low pass 500Hz filter. After recording, raw data were IIR filtered (high pass 20Hz, low pass 500Hz, notch 50Hz) and rectified. Filtered EMG data were timelocked to the E-Prime presented instruction screens and then downsampled to 10Hz.

The muscles assessed were M. corrugator supercilii, M. levator labii superioris, M. zygomaticus major and M. masseter. Before attaching the bipolar electrodes on the left side of the face, the face was cleaned using a skin cleanser (Cetaphil, Johnson & Johnson), the skin was abraded, rubbed with an alcohol-swab and then electrode gel was rubbed into the recording site. The electrodes were positioned using established guidelines [29,30] and were consistent with previous studies by PRC [18,19]. In order to check that the electrodes were

recording correctly, at the commencement of a testing session participants were asked to wrinkle their eyebrows (corrugator), wrinkle their nose (levator), smile (zygomaticus), and clench their jaw (masseter). No additional unreported physiological measurements were recorded in this study.

Subjective liking ratings

Participants provided a pair of subjective ratings for each solution that they sampled in the tasting and rating block. Affect ratings used the instruction “please rate your liking...” and presented a 100-point labelled affective magnitude (LAM) scale [31] with 11 anchors distributed across the range from +50 “greatest imaginable like” to -50 “greatest imaginable dislike.” Intensity ratings used the instruction “please rate the intensity...” and presented a 100-point quasi-logarithmic labelled magnitude scale (LMS[32]) with 6 anchors ranging from “Strongest Imaginable” at the maximum of the scale to “Barely Detectable” just above the zero point.

The LAM was always presented first and participants responded to both scales by using the mouse to click on the scale. Brief feedback was given by displaying a horizontal line on the scale where the participant had clicked for 100ms.

Only the affective ratings collected using the LAM scale are presented in the present report. There was a linear relationship between LMS ratings and increasing solution concentration and this will be reported elsewhere. There were no additional subjective responses collected in this experiment.

Data analysis

Electromyographic change scores were calculated by subtracting the mean muscle activity level during the 500ms period prior to the start of each tasting trial. With this transformation,

209 positive changescore values represent an increase in muscle activity in response to liquid
210 (increased muscle contraction) and negative values represent relaxation of muscle in response
211 to the liquid; zero represents no muscle activity change from baseline.

212 The EMG change scores and the rating data of four facial muscles with sweet and bitter
213 stimuli were evaluated using two separate analysis strategies. First, for the rating data an
214 analysis of variance with repeated measures (Solution Type: Bitter/Sweet; Concentration:
215 Water/Low/Medium/High) was conducted for the LAM ratings. Second, data were entered
216 into a linear mixed model to predict hedonic liking using facial muscle activity. A mixed
217 model was chosen because it provides substantial advantages over regression and correlation
218 analyses: similar to a regression or correlation analysis, it provides an estimate of the
219 relationship between muscle activity and ratings; but it allows a model to be specified that
220 includes multiple observations per participant and replaces the traditional approach of
221 running a separate participant and item analyses, or ranking participant responses and
222 calculating a correlation; it enables random effects to be specified within the model and this
223 can explain more variance within the data than traditional measures (we use a random
224 intercept for participants to account for individual differences in sweet and bitter liking).

225 In summary, the ANOVA assesses whether the participants were able to discriminate the
226 different solution concentrations. Whereas, the mixed model is being used to describe how
227 much of a change in subjective liking can be explained by different muscles in response to
228 the liquids.

Results

Liking ratings

The LAM affect ratings from the rating block for bitter and sweet stimuli at different concentration levels were entered into a repeated measures ANOVA using SPSS version 23 by BL. Greenhouse-Geisser adjustments were made because of a violation of sphericity, although this made no qualitative difference to the significance tests. There was an interaction between solution type and concentration, $F(1.85, 33.33) = 30.30, p < 0.001, \eta^2 = 0.63$). Based on this interaction, the sweet and bitter solutions were entered into separate analyses. These ANOVA revealed that LAM ratings of bitter solutions decreased linearly as the concentration increased, $F(1.84, 33.07) = 111.45, p < 0.001, \eta^2 = 0.86$. In contrast, LAM ratings for sweet solutions increased relative to water, but the mean liking did not show the linear pattern of the bitter solutions, $F(1.64, 29.57) = 0.86, p = 0.41, \eta^2 = 0.05$ because the higher concentrations were disliked by some participants. The mean LAM ratings are shown in Fig 1.

Fig 1. LAM affect ratings for three concentrations of bitter and sweet solutions. Ratings are mean responses of three tastings for each solution. Points are horizontal jittered to reduce over plotting.

Modelling of EMG activity and LAM rating

Data were entered into a series of linear mixed models. All modelling was by PRC using R version 3.3.1 [33] and the models presented were fit using the LME4 package version 1.1-13 [34], although these results were replicated by BL using SPSS version 23 and by PRC using a Bayesian approach with the RStan package [35]. The dataset is available on Zenodo [36].

The model building strategy addressed the hypothesis that muscle activity would explain substantial variance in the LAM liking rating. First, a restricted model was specified that contained only random effects. This model served as the null model to compare with a full model that included muscle activity as fixed effects. The random effects included in the restricted and full models were participant, solution type, and solution concentration. Other models were considered that did not include solution type and concentration as random effects and these results are included in the supplementary material [37]. All random effects were random intercepts only. This strategy provides a conservative test of the hypothesized relationship between muscle activity and ratings because the large unique variance associated with the solution type and concentration has already been explained by the random effects and the remaining variance that can be explained by muscle activity will be unique. Separate models were specified for the tasting and rating blocks and within these blocks there was a separate model calculated for the emptying, swirling, and thinking phase. This resulted in six separate models. The dependent variable for each model was the mean of three LAM ratings for each concentration of the bitter and sweet liquids.

267 This provides two opportunities to predict the final LAM rating, once using the tasting only
268 data and once using the tasting and rating data: the tasting only data was expected to have
269 slightly weaker predictive power because there was a longer duration between these tastings
270 and the rating task. To address the study hypotheses, a comparison was made between the
271 model that contained only random effects (null model) and the model that included the three
272 muscles as fixed effects as well as the random effects (full model). Thus, full models
273 included the mean corrugator, levator, and zygomaticus muscle activity for that tasting phase.
274 A maximum likelihood estimation approach was selected so that models could be compared
275 using a chi square test on the model likelihood. Confidence intervals for fixed effects were
276 calculated using parametric bootstrapping based on 10,000 samples from the fitted models;
277 from this data, the 2.5% and 97.5% percentiles were extracted to give an estimate of the 95%
278 confidence level for each muscle.

279 Models were based on 19 participant's data for 8 solution type and concentration
280 combinations (152 observations). Although participants tasted each liquid three times in both
281 the tasting and rating blocks, muscle activity and ratings for these three replicates were
282 averaged to simplify the models. Tastings where the fixation muscle activity was extreme
283 compared to the participant's mean fixation activity were excluded, but because there were
284 three replicates of each solution per block this strategy resulted in minimal missing data (1
285 missing observation from the total of 152 for some models).

286 Examination of multivariate outliers based on Mahalanobis distances resulted in between one
287 and six observations being identified as extreme depending on the block and phase that was
288 being considered. The main outcome of removal of multivariate outliers was that there were
289 slight differences in the estimation of fixed effects owing to the removal of these influential
290 values and the slight reduction in power with there being fewer degrees of freedom. The
291 analyses reported below do not exclude multivariate outliers, but for two models (swirling

while tasting; swirling while tasting then rating) the effect of outlier removal is discussed when the results are presented.

All restricted (null) models and full models converged normally. A visual inspection of q-q plots for these models revealed that residuals were stochastic and did not violate assumptions of homoscedasticity or normality.

Tasting block

All three phases of the tasting block resulted in an improved likelihood when the fixed effects of corrugator, levator, and zygomaticus muscle activity were simultaneously entered into the model, $\chi^2_{\text{Emptying}}(3) = 9.6, p = 0.02$; $\chi^2_{\text{Swirling}}(3) = 12.9, p = 0.005$; $\chi^2_{\text{Thinking}}(3) = 16.4, p < 0.001$. Adding masseter muscle activity as a fixed effect did not substantially improve the model likelihood compared with the models that contained corrugator, levator, and zygomaticus (all $\chi^2 < 1.2, p > .29$) and these models are not discussed further (but are provided in the supplementary material). The fixed effects are described below.

For the emptying phase, only corrugator activity reliably predicted LAM, with a single unit increase (muscle activity doubling compared with relaxed face prior to the solution tasting) in corrugator resulting in a decrease in liking by $-5.70 [-9.57; -1.84]$, $\beta = -.44 [-0.73; -0.15]$ points on the 100-point LAM scale. The direction of the effects for zygomaticus and levator were as predicted, with levator activity associated with a decrease in liking and zygomaticus with an increase in liking, although both sets of confidence intervals overlapped zero. For the swirling phase, all three effects were again in the predicted direction, but only zygomaticus reliably predicted change in LAM with an increase in LAM rating of $2.43 [0.10; 4.78]$, $\beta = .11 [0.01; 0.22]$ per unit increase in muscle activity. Again, corrugator and levator effects were in the predicted direction, but with confidence intervals that slightly overlapped zero. Removal of 6 multivariate outliers for this model resulted in the corrugator predicting $-4.06 [-7.04; -$

0.95] change in LAM and being the only significant predictor of LAM, with the zygomaticus effect reduced to 1.58 [-1.09; 4.28]. For the thinking phase, all three muscles acted in the predicted direction, but with only zygomaticus reaching statistical significance, for which there was a 3.52 [0.22, 6.94], $\beta=0.16$ [0.01, 0.32] increase in LAM. As with previous phases, both corrugator and levator effects were in the predicted direction, but again both confidence intervals overlapped zero. Fixed effects are plotted in Figure 2.

Fig 2. Change in affective ratings of bitter and sweet solutions predicted by muscle activity at three oral processing stages. Increased corrugator and levator activity predicts a decrease in LAM affect scores, but increased zygomaticus activity predicts an increase. Data are mixed model fixed effects while tasting only and when tasting and rating and represent the change in LAM explained by each muscle. Error bars are 95% confidence intervals calculated from the 2.5% and 97.5% percentiles from 10,000 bootstrapped samples of the parametric distribution extracted from the fitted models.

Tasting and rating block

Similar to the tasting only block, all three full models including the fixed effects of corrugator, levator, and zygomaticus mean activity resulted in an improved model fit compared with the restricted model containing only random effects, $\chi^2_{\text{Emptying}}(3) = 12.67, p = 0.005$; $\chi^2_{\text{Swirling}}(3) = 21.07, p < 0.001$; $\chi^2_{\text{Thinking}}(3) = 27.38, p < 0.001$. Again, adding masseter activity as a fixed effect had a negligible influence on the model likelihood (all $\chi^2 < 2.4, p > .13$) and this muscle was not included in the models described below. The overall pattern of results for this block was identical to the tasting only block, with all fixed effects in the predicted direction.

During the emptying phase, all three muscles predicted significant change in LAM ratings.

An increase in corrugator activity resulted in decreasing liking, $-2.89 [-5.46, -0.36], \beta = -0.22 [-0.42, -0.03]$; an increase in levator activity resulted in decreased liking, $-2.91 [-4.93, -0.84], \beta = -0.26 [-0.44, -0.07]$, and an increase in zygomaticus activity in increased LAM ratings $4.99 [0.67, 9.24], \beta = 0.23 [0.03, 0.43]$. The direction of these effects was identical for the swirling phase, but the only muscle significantly predicting change in LAM rating was the levator for which an increase in activity resulted in a decrease in liking, $-2.81 [-4.64, -0.96], \beta = -0.25 [-0.41, -0.09]$; although the direction of the effects were as predicted, there was a slight overlap with zero for the confidence intervals for both corrugator and zygomaticus. Removal of 2 multivariate outliers resulted in a slight increase in the size of the effect for levator to $-3.11 [-5.09, -1.27]$ and the corrugator reaching statistical significance by predicting $-3.48 [-5.78, -1.03]$ decrease in liking. Finally, the same direction of effects were observed for the thinking phase, with levator predicting a decrease of $-5.22 [-8.28, -2.17], \beta = -0.46 [-0.74, -0.19]$ points on the LAM scale. For this phase, the corrugator effect was less pronounced with its confidence intervals overlapping zero, meanwhile there was only a slight overlap of the confidence intervals for zygomaticus. These results are plotted in Fig 2.

Additional models considered

As discussed earlier, an additional set of models were considered that included participant as the only random effect. These models produced a pattern of directional fixed effects that matched the above models, but the confidence intervals for these fixed effects were less likely to overlap zero. Not including solution type and concentration as random effects results in stronger fixed effects partly because of increased power available in these models, but also because the correlated structure of the data has not been accounted for in the model. But these models should be interpreted with caution because this underspecified structure results in a non-normal distribution of residuals. This model structure would likely be helpful for a more homogeneous set of food samples for which the enhanced power would provide increased opportunity to detect effects and there would be less risk of non-normal residuals. These models are included in the supplementary material [37].

Discussion

When tasting bitter and sweet liquids, affective facial muscle activity predicts liking or disliking of that solution. The results provided full or partial support for all three hypotheses. Supporting H_1 , corrugator supercilii and levator labii superioris activity predicted decreased liking and zygomaticus major activity predicted increased liking. While the magnitude of these effects fluctuated for the different phases of oral processing and for the two different blocks, there is sufficient evidence to be confident that these muscles are useful predictors of hedonic responses to food. These facial muscles can explain unique change in liking even after the variance resulting from participant individual differences, solution type, and concentration have been statistically controlled.

Although the relationship between muscle activity and liking did vary, the direction of these effects was identical and the magnitudes of these effects were similar across the different phases of oral processing supporting H₂. An important finding was that muscle activity could predict later liking ratings even when first emptying solutions into the mouth. This suggests that in food product evaluation it might be valuable to assess first impressions when encountering novel foods as well as the overall experience, especially in complex foods that change in texture and taste throughout the dynamic consumption process.

There was partial support for H₃, because the relationship between emotional facial muscle activity and liking varied depending on the task (tasting only or tasting and rating). Again, the pattern of facial muscle activity was consistent across tasks, but there were slight differences in the magnitude of these effects. For example, levator consistently predicted the liking rating during the tasting and rating block, but the confidence intervals always had a slight overlap with zero for the tasting only block. It is unsurprising that the muscles were stronger predictors in the tasting and rating block because the muscle activity was directly related to the sample that was being rated. During the tasting only block, the each sample was being tasted amongst other samples and these might have had slight influences on the participant's affective state (for example, a medium concentration bitter solution tastes subjectively more bitter following another mild concentration bitter solution than following a strong concentration bitter solution). It is promising that muscle activity while tasting a set of samples without being asked to give a rating can predict ratings that occur sometime later during re-exposure to the same foods—this means that facial EMG is indeed a non-interruptive measure of hedonic responses to food stimuli. This method of initial exposure to stimuli without ratings being used to predict later re-exposure to stimuli with ratings has been used previously to investigate moral judgments [18] and fluency of interaction [19], and this current results suggest that it is a robust method to assess liking of foods.

There was some variability for the relationship between muscle activity and liking and there are two main reasons for this lack of consistency: first, the study was somewhat low powered and this resulted in wide confidence intervals; second, including random intercepts for solution type and concentration explained a large proportion of the variability in liking, making this a conservative test of the relationship between muscle activity and liking. Within the supplementary materials [37], an additional set of less conservative models are presented that do not include random effects for solution type and concentration. These analyses reveal a stronger relationship between muscle activity and LAM ratings. The difference between these two sets of analyses is that for the full models there is only minimal variability in subjective ratings available to be explained by fixed effects because there is a correlation between ratings and solution type and ratings and concentration; the muscle activity fixed effects are explaining *unique* variance that has not already been accounted for by the solution type and concentration, so the effects are small; in contrast, for the models that do not include solution type and concentration as random effects there is greater variance in ratings remaining that can be explained by muscle activity. Neither analysis strategy should be discounted [38] because both provide valuable insights into the relationship between facial muscle activity and subjective liking of liquid solutions.

The reported data analyses were restricted to testing a set of a priori planned hypotheses and for this reason there are no exploratory analyses reported. The full study dataset includes high temporal resolution data recorded at 2KHz during tasting and it is likely that the relationship between liking and muscle activity will vary throughout the sensory experience. Future analyses will explore the timecourse of affective responses to liquids. For example, bitter liquids are likely to evoke rapid aversive responses and data recorded early in the tasting might result in stronger predictions of disliking for bitter liquids.

The masseter muscle was included in this study to assess whether affective responses to liquid solutions would be reflected in functional muscle activity (e.g. increased jaw clenching for bitter liquids). Masseter activity is important because it is the main functional muscle related to chewing and jaw closing [3,39]. In this study the masseter was active when first closing the mouth and also during jaw clenching. While there was no appreciable relationship between masseter activity and affective ratings, this might be different for oral processing of solid and semisolid foods.

We have presented a statistically robust method of analysing facial muscle activity during oral processing of liquids. The linear mixed model approach that was adopted in this research has advantages compared with existing analyses that used combinations of correlations, t-tests, and analysis of variance and simple regression. When evaluating affective responses or preferences, there is often considerable variation in participants responses to the stimuli and this is particularly the case with food stimuli because of individual differences: such as sweetness preference [40,41], bitter sensitivity [41,42], social influence [43], cultural norms[18,44], and past experiences [45]. This study demonstrates that linear mixed models are an appropriate analysis tool for research investigating hedonic responses to foods because they allow for individual differences within the data.

Conclusions

Throughout the study, muscles associated with facial expressions of negative affective states, corrugator (frowning) and levator (disgust) predicted a decrease in liking ratings; whereas, a muscle associated with positive affect, zygomaticus (smiling), predicted an increase in liking ratings. Facial muscle activity is a useful measure when assessing hedonic responses to liquid solutions. This non-interruptive method has potential for use in product evaluation and can explain subtle differences in liking throughout different stages of oral processing of liquids.

450 This technique is a promising tool for developing insights into liking and provides a window
451 on an individual's hedonic experiences with food.

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