Corticobulbar Activity and Motivational Arousal in Healthy Participants

Francesca Ferraioli[1], Francesco Tomaiuolo[2], Alessandra Falzone[1], Angelo Labate[3], Salvatore Massimiliano Cardali[4], Simona Massimino[1], Fabrizio Esposito[5], Luigi Trojano[6], Carmelo M Vicario[1]

Affiliations:

[1] Laboratory of Cognitive and Social Neuroscience, Department of Cognitive Science (COSPECS), University of Messina, 98121 Messina, Italy

[2] Department of Clinical and Experimental Sciences biomedical, dental and imaging morphological and functional, 98166 Messina, Italy

[3] Neurophysiology and Movement Disorders Unit, University of Messina, Messina, Italy.

[4] Department of Neurosurgery, Azienda Ospedaliera Papardo, University of Messina, Italy.

[5] Department of Advanced Medical and Surgical Sciences, MRI Research Center, Università degli Studi della Campania Luigi Vanvitelli, Naples, Italy.

[6] Department of Psychology, University of Campania Luigi Vanvitelli, Caserta, Italy

E-mail addresses:

Francesca Ferraioli: francaferr.ferraioli@gmail.com / francesca.ferraioli@unime.it;

Francesco Tomaiuolo: francesco.tomaiuolo@unime.it;

Alessandra Falzone: alessandra.falzone@unime.it;

Angelo Labate: angelo.labate@unime.it;

Salvatore Massimiliano Cardali: salvatore.cardali@unime.it;

Simona Massimino: simona.massimino@unime.it;

Fabrizio Esposito: fabrizio.esposito@unicampania.it;

Luigi Trojano: luigi.trojano@unicampania.it;

Carmelo M Vicario: carmelomario.vicario@unime.it.

Abstract

Background. Corticobulbar (CB) projections linking tongue/submental effectors to motor cortex are implicated in reward processing and motivational arousal (Alipour et al., 2002; Kringelbach et al., 2003; Kringelbach, 2005; O'Doherty, 2004; Volkow et al., 2011; 2017). Submental muscle (SbM) surface EMG may thus provide a convenient physiological window on motivational states during foods selection (Sato et al., 2021; Ferraioli and Vicario 2024). **Objective.** To test, in healthy participants, whether SbM activity recorded during an immersive virtual-reality (VR) supermarket varies as a function of food motivational category (Daily, Hedonic, Dislike) and whether SbM contributes to the prediction of self-reported preference, along with personality traits, like impulsivity in monetary choice, measured by Monetary Choice Questionnaire (MCQ; Kaplan et al., 2016). **Methods.** Fourteen adults completed a VR shopping task selecting 10 products per three different conditions. SbM was recorded continuously and summarized within pre-selection (−550/−200 ms) and post-selection (T0/+550 ms) windows, as specified in our published protocol (Ferraioli et al., 2025). Linear mixed-effects models (LME) examined effects of Condition and Phase on SbM. A separate LME predicted Preference from SbM, Condition, and impulsivity (MCQ). **Results.** SbM was higher in Hedonic vs Daily ($\beta=0.342$, $p=.022$), with no main effect of Phase ($p=.774$) and no Condition×Phase interactions. Preference was positively associated with SbM ($\beta=0.441$, $p=.043$) and strongly reduced in Dislike ($\beta=-5.760$, $p<.001$); MCQ had no effect. **Conclusions.** Our preliminary analyses on an ecologically valid VR environment, showed SbM differentiates motivational categories and independently predicts reported preference, supporting SbM as a candidate biomarker of motivational arousal and complementing the broader CB-excitability program (Ferraioli et al., 2025).

Keywords: corticobulbar tract; submental EMG (SbM); virtual reality; food preference; motivational arousal; linear mixed-effects models.

Introduction

Motivational arousal—the vigor with which organisms approach or avoid stimuli—depends critically on dopaminergic circuitry (Berridge, 2004; Salamone & Correa, 2012). The corticobulbar (CB) tract, conveying signals from motor cortex to orofacial effectors, sits anatomically and functionally at this interface (Love & Webb, 1992; Gonzalez-Fernandez et al., 2018; Wilmskoetter, Daniels, & Miller, 2020). Prior evidence shows that (i) excitability within tongue motor cortex and (ii) SbM activation are modulated by hedonic and aversive cues (Vicario et al., 2014; Vicario et al., 2022; Sato et al., 2021). CB-related pathways are tightly intertwined with reward valuation mechanisms in orbitofrontal and limbic systems (Alipour et al., 2002; Kringelbach et al., 2003; Kringelbach, 2005; O'Doherty, 2004), suggesting that orofacial preparatory responses may provide an assay of motivational engagement. In naturalistic choice, eye-movement and VR studies link motivational relevance to attention and overt preference (Gidlöf et al., 2017; Melendrez-Ruiz et al., 2022). These converging observations motivated the two-study program formally described in our protocol (Ferraioli et al., 2025). Here we report on Study 1 preliminary results in healthy participants. From a measurement standpoint, SbM EMG offers several advantages. Submental muscles (suprahyoid group) participate in preparatory oral actions and can be monitored non-invasively with high temporal resolution (Wilmskoetter et al., 2020). Conceptually, appetitive or aversive value may recruit subtle orofacial preparatory responses, rendering SbM a sensitive read-out of motivational engagement even when overt facial expressions are minimal (Ferraioli and Vicario, 2024).

Methods

Participants

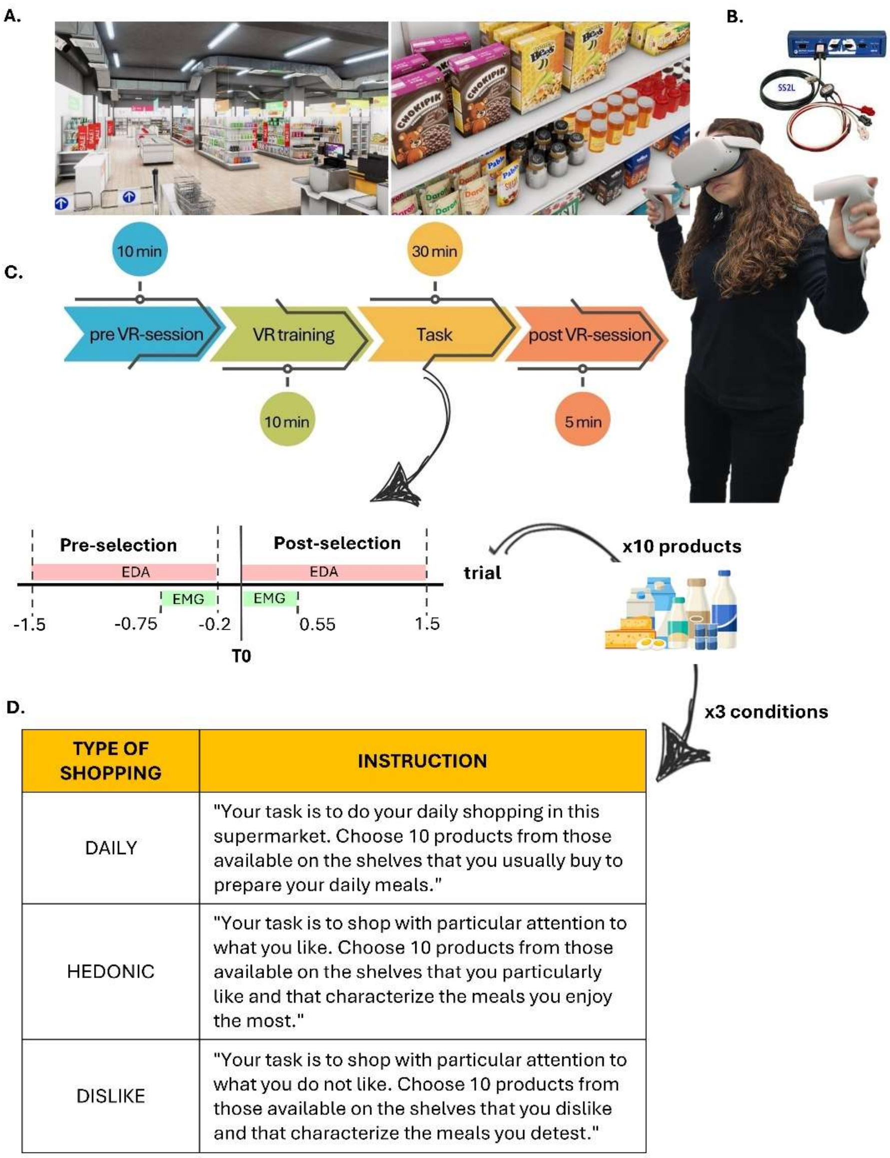
Fourteen healthy adults (mean age 22.8 ± 6.5 years; 8 female) completed the pilot. Exclusion criteria included neurological/psychiatric disorders, severe cybersickness, or uncorrected visual deficits. Participants provided written informed consent under institutional ethical oversight.

Table 1. Sample characteristics (Study 1 pilot)

Characteristic	Value
N (participants)	14
Age, years (mean ± SD)	22.8 ± 6.5
Sex, n (%)	8 female (57%), 6 male (43%)
Handedness	Right-handed (self-report)
Inclusion	Normal or corrected vision; no neurological/psychiatric disorders
Exclusion	Severe cybersickness; uncorrected visual deficits

VR apparatus and task

The supermarket environment (Unity 3D) was presented via Oculus Quest 2 with hand-held controllers, the headset was connected to the PC for virtual navigation as Rift link. As outlined in **Figure 1**, participants first completed a pre-VR session (~10 min) including consent, screening, and baseline measures. They then underwent a brief VR training (~10 min) to familiarize themselves with navigation and object selection in the supermarket environment. The task (~30 min) comprised three shopping blocks—Daily, Hedonic, and Dislike—whose order was counterbalanced across participants. In each block, participants were instructed to select 10 products matching the block's criterion (Daily = usual staple items; Hedonic = personally liked/indulgent items; Dislike = personally disliked items, see **Figure 1, D.**). After each selection, they rated pleasantness, perceived nutritional value, desire to consume, and purchase probability (1–10 Likert). Physiological activity was recorded continuously. Submental EMG (SbM) was time-locked to movement onset (T0) and summarized in two windows: Pre-selection (−550 to −200 ms; motor programming) and Post-selection (0 to +550 ms; conscious choice). Electrodermal activity (EDA) was also acquired in parallel. A post-VR session (~5 min) followed, including the Presence Questionnaire and debriefing. Before VR-session MCQ (Kaplan et al., 2016) along with demographic information were also collected.



TYPE OF SHOPPING	INSTRUCTION
DAILY	"Your task is to do your daily shopping in this supermarket. Choose 10 products from those available on the shelves that you usually buy to prepare your daily meals."
HEDONIC	"Your task is to shop with particular attention to what you like. Choose 10 products from those available on the shelves that you particularly like and that characterize the meals you enjoy the most."
DISLIKE	"Your task is to shop with particular attention to what you do not like. Choose 10 products from those available on the shelves that you dislike and that characterize the meals you detest."

Figure 1. Experimental procedure and task flow. (**A.**) Views of the immersive VR supermarket. (**B.**) Recording set-up: SbM sEMG and VR headset/controllers. (**C.**) Timeline showing pre-VR session, VR training, task, and post-VR session; lower panel depicts analysis windows for EDA and SbM relative to movement onset (T0). (**D.**) Task instructions for the three shopping conditions (Daily, Hedonic, Dislike). Adapted from the published study protocol Ferraioli et al. (2025).

Materials and instruments

sEMG system and electrodes. BIOPAC MP-series amplifier (sampling 1 kHz), pre-gelled Ag/AgCl surface electrodes over the submental (suprahyoid) region. Signal synchronization with VR events was achieved by custom markers.

Acquisition software. AcqKnowledge for recording; data exported to MATLAB/R for preprocessing and statistics.

EMG acquisition and preprocessing

Surface EMG from the SbM was acquired at 1 kHz. Signals were notch-filtered at 50 Hz, band-pass filtered 25–400 Hz (4th-order Butterworth), rectified and RMS-smoothed with a 50-ms window, and baseline-normalized to a 60-s resting period before the task, following the published protocol (Ferraioli et al., 2025). Event timing was synchronized to VR via customized MATLAB script. Two analysis windows were defined relative to movement onset (T0): Pre-selection (−550/−200 ms; motor programming) and Post-selection (0/+550 ms; conscious choice) (Ferraioli et al., 2025).

Outcomes

Primary physiological outcomes were SbM means amplitude within each window for each product. Behavioral outcomes were item-wise preference ratings. Trait impulsivity was indexed by MCQ.

Statistical analysis

Data were organized in long format (84 observations; 1 outlier removed → 83). Linear Mixed Effects (LME) models on SbM included fixed effects Condition (Daily, Hedonic, Dislike) and Phase (Pre, Post), their interaction, and a random intercept for participant. A predictive LME of Preference included fixed effects SbM, Condition, MCQ, and participant random intercept. Analytic choices align with the preregistered protocol (Ferraioli et al., 2025).

Results

Distributional checks

Shapiro–Wilk tests suggested approximate normality for Daily and Dislike, with deviations in Hedonic; LME is robust to such deviations under balanced designs. Outlier removal was minimal (83/84 retained).

Linear mixed-effects analyses

We fitted two complementary LME models addressing, respectively, (i) whether SbM varies with motivational category and analysis Phase, and (ii) whether SbM predicts Preference over and above Condition and impulsivity (MCQ). Both models included a random intercept for participants. In Figure 2 below is presented the Preference model (Figure 2, A.) along with bars chart for SbM means activity organized in conditions and phases (Figure 2, B.).

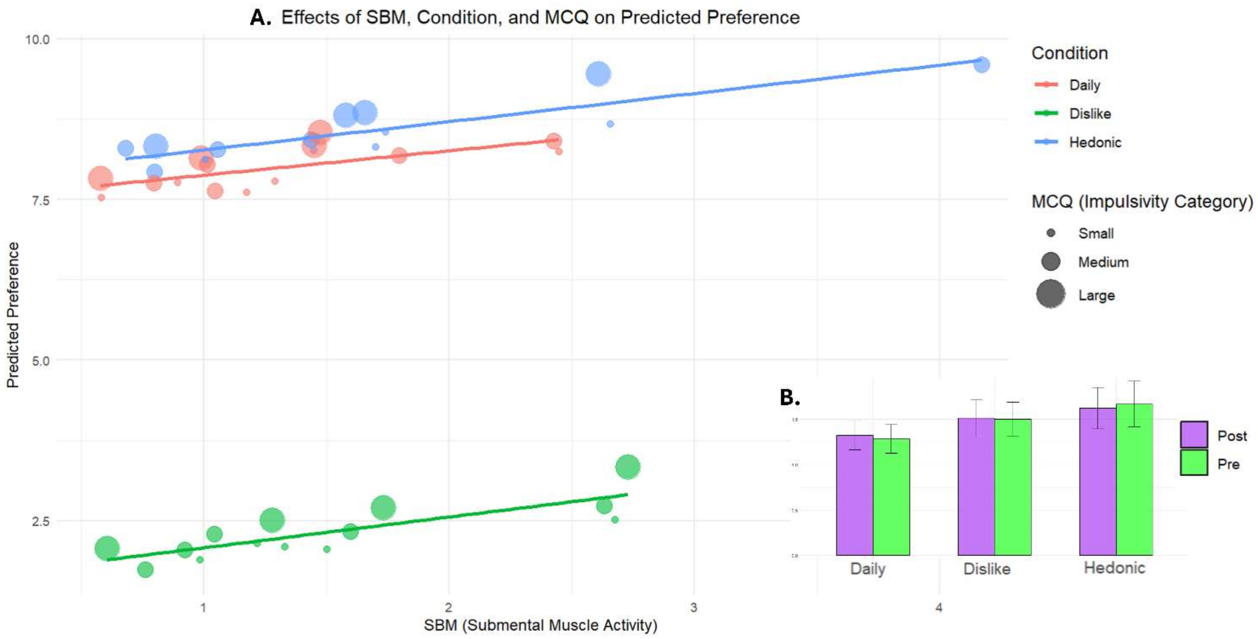


Figure 2. Combined results panel. (**A.**) Effects of SbM, Condition, and impulsivity (MCQ) on predicted preference, and (**B.**) mean SbM with standard errors across Condition × Phase (right). Points are sized by MCQ category: Large, Medium and Short; regression lines are estimated within condition. Error bars reflect the standard error of the sample.

In the physiological "manipulation-check" model with SbM as the dependent variable, SbM differed by category but not by phase. The intercept was 1.324 (SE 0.200, $t = 6.62$, $p < .001$). Relative to Daily items, Hedonic items were associated with higher SbM ($\beta = 0.342$, SE 0.146, $t = 2.35$, $p = .022$), whereas Dislike did not differ significantly ($\beta = 0.189$, SE 0.142, $t = 1.33$, $p = .189$). The temporal window—Pre-selection versus Post-selection—showed no main effect ($\beta = -0.041$, SE 0.142, $t = -0.29$, $p = .774$), and none of the Condition × Phase interactions reached significance (all $p \geq .835$). Taken together, these results indicate that SbM is selectively elevated for hedonic choices and that, within the present windows, its amplitude is relatively stable around the moment of selection.

The predictive model treated preference as the outcome and included continuous SbM, category, and MCQ impulsivity as fixed effects reach significance only in the Pre-selection phase. In particular, preference increased with SbM ($\beta = 0.441$, SE 0.207, $t = 2.14$, $p = .043$), indicating that trials with stronger submental activation tended to receive higher ratings. Category exerted a large contextual influence: Dislike items were associated with markedly lower preference than Daily ($\beta = -5.760$, SE 0.318, $t = -18.11$, $p < .001$), while Hedonic did not differ reliably from Daily ($\beta = 0.409$, SE 0.325, $t = 1.26$, $p = .220$). Impulsivity made no detectable contribution (MCQ: $\beta = 0.064$, SE 2.246, $t = 0.03$, $p = .978$). Overall fit indices were AIC = 118.79, BIC = 130.07, and LogLik = −52.40 (42 observations from 14 participants).

In summary, the first model confirms that SbM is sensitive to the motivational value of the items (higher for hedonic choices), while the second shows that SbM carries predictive information about subjective preference beyond category membership and trait impulsivity. Together they support the interpretation of SbM as a physiologically grounded marker of motivational engagement during immersive choice.

Discussion

This pilot indicates that spontaneous submental EMG (SbM) recorded in an immersive supermarket task is sensitive to the motivational value of food items and carries information that is useful for explaining the preference participants ultimately report. The increase observed for hedonic items fits the broader view that appetitive valuation recruits subtle orofacial preparatory states, consistent with links between reward processes and bulbar motor control (Kringelbach, 2005; Vicario et al., 2014; Sato et al., 2021; Ferraioli & Vicario, 2024; see also Ferraioli et al., 2025). In keeping with this account, the mixed-effects model showed that higher SbM tracked higher preference ratings even after accounting for category and trait impulsivity, suggesting that SbM indexes a latent component of motivational engagement not fully captured by self-report.

A critical temporal qualification emerged from the analyses: the predictive link between SbM and preference was present only in the pre-selection window (−550 to −200 ms), that is, before action initiation when motor programming unfolds (Braun, Wessler, and Friese 2021; Libet et al. 1983; Lumer 2014). In this anticipatory phase, valuation signals are plausibly translated into orofacial preparatory activity that facilitates the upcoming choice, making SbM a sensitive read-out of momentary motivational drive. When the same model was applied to the post-selection window (0 to +550 ms), the association was not reliable, suggesting that once a choice is executed, decisional and sensory consequences may dilute or overwrite the preparatory motor signal. Taken together, these findings point to anticipatory corticobulbar engagement as the most informative physiological substrate for modeling subjective preference in immersive contexts.

Finally, the pattern observed here provides an empirical bridge to our broader program on corticobulbar markers. By demonstrating sensitivity to motivational category and predictive value specifically during motor preparation, Study 1 offers mechanistic constraints that can inform the interpretation of corticobulbar excitability measures in broader populations and guide the design of tasks, consumer as well as clinical contexts that maximize physiological sensitivity to motivational states.

Limitations and future directions

The study is preliminary, with a small sample, and reliance on two brief analysis windows, which limit generalizability; SbM is also susceptible to electrode placement and swallow/speech artifacts despite precautions. Future work should pre-register analyses, increase sample size, and incorporate covariates that may modulate motivational arousal (e.g., hunger, BMI), explore hierarchical (including non-linear) specifications, and integrate additional physiological channels to test whether combining anticipatory corticobulbar activity with complementary signals further improve trial-wise prediction. These extensions will support translational comparisons with corticobulbar excitability in Parkinson's disease and refine the use of SbM as a practical biomarker as proxy on motivational engagement.

Author contributions

FF: Methodology, Writing – original draft, Writing – review & editing, Data curation, Formal analysis, Project administration. FT: Conceptualization, Funding acquisition, Supervision, Writing – review & editing. AF: Conceptualization, Writing – review & editing. AL: Conceptualization, Funding acquisition, Writing – review & editing. SC: Project administration, Supervision, Validation. SM: Data curation, Writing – review & editing. FE: Supervision, Writing – review & editing. LT: Supervision, Writing – review & editing. CV: Conceptualization, Funding acquisition, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing.

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References

Alipour, M., Chen, Y., & Jürgens, U. (2002). Anterograde projections of the motorcortical tongue area in the saddle-back tamarin (*Saguinus fuscicollis*). *Brain, Behavior and Evolution, 60*(2), 101–116. https://doi.org/10.1159/000065205

Baik, J.-H. (2013). Dopamine signaling in reward-related behaviors. *Frontiers in Neural Circuits*. https://doi.org/10.3389/fncir.2013.00152

Braun, M. N., Wessler, J., & Friese, M. (2021). A meta-analysis of Libet-style experiments. *Neuroscience & Biobehavioral Reviews, 128*, 182–198. https://doi.org/10.1016/j.neubiorev.2021.06.018

Berridge, K. C. (2004). Motivation concepts in behavioral neuroscience. *Physiology & Behavior, 81*(2), 179–209. https://doi.org/10.1016/j.physbeh.2004.02.004

Ferraioli, F., & Vicario, C. M. (2024). Predicting consumers' purchase through the corticobulbar tract: A novel psychometric tool at the service of neuromarketing? *Reti, saperi, linguaggi – Italian Journal of Cognitive Sciences*, Issue 1, 155–164. https://doi.org/10.12832/113803

Ferraioli, F., Tomaiuolo, F., Falzone, A. M., Labate, A., Cardali, S. M., Massimino, S., Esposito, F., Germanò, A., Trojano, L., & Vicario, C. M. (2025). Corticobulbar activity in healthy humans and Parkinson's disease: A study protocol for a novel biomarker of motivational arousal. *Frontiers in Psychology*, 16, 1573534. https://doi.org/10.3389/fpsyg.2025.1573534

Gonzalez-Fernandez, M., Langton-Frost, N., Wright, A. N., Karagiorgos, E., & Bahouth, M. N. (2018). Swallowing Disorders After Stroke. In *Stroke Rehabilitation* (pp. 61-70). Elsevier. https://doi.org/10.1016/B978-0-323-55381-0.00004-4

Kaplan, B. A., Amlung, M., Reed, D. D., Jarmolowicz, D. P., McKerchar, T. L., & Lemley, S. M. (2016). Automating Scoring of Delay Discounting for the 21- and 27-Item Monetary Choice Questionnaires. *The Behavior analyst*, *39*(2), 293–304. https://doi.org/10.1007/s40614-016-0070-9

Kringelbach, M. L. (2005). The human orbitofrontal cortex: Linking reward to hedonic experience. *Nature Reviews Neuroscience*. https://doi.org/10.1038/nrn1747

Kringelbach, M. L., O'Doherty, J., Rolls, E. T., & Andrews, C. (2003). Activation of the human orbitofrontal cortex to reward. *Cerebral Cortex*. https://doi.org/10.1093/cercor/13.10.1064

Libet, B., Gleason, C. A., Wright, E. W., & Pearl, D. K. (1983). Time of conscious intention to act in relation to onset of cerebral activity (readiness-potential): The unconscious initiation of a freely voluntary act. *Brain, 106*(3), 623–642. https://doi.org/10.1093/brain/106.3.623

Love, Russell J, and Wanda G Webb. *Neurology for the Speech-Language Pathologist*. 3rd ed. Boston: Butterworth-Heinemann, 1996. Print.

Lumer, C. (2014). The effectiveness of intentions – A critique of Wegner. In C. Lumer (Ed.), *Morality in Times of Naturalising the Mind* (pp. 105–124). De Gruyter. https://doi.org/10.1515/9781614518013.105

Melendrez-Ruiz, J., Velasco-Borrego, I., & Arboleda, A. M. (2022). Virtual supermarkets to study food choice. *Food Quality and Preference*. https://doi.org/10.1016/j.foodqual.2021.104510

O'Doherty, J. P. (2004). Reward representations and learning in the human brain. *Current Opinion in Neurobiology*. https://doi.org/10.1016/j.conb.2004.10.016

Salamone, J. D., & Correa, M. (2012). The mysterious motivational functions of mesolimbic dopamine. *Neuron, 76*(3), 470–485. https://doi.org/10.1016/j.neuron.2012.10.021

Sato, W., et al. (2021). Electromyographic activity associated with hedonic responses to food. *Nutrients*. https://doi.org/10.3390/nu13010011

Vicario, C. M., Salehinejad, M. A., Mosayebi-Samani, M., Maezawa, H., Avenanti, A., & Nitsche, M. A. (2020). Transcranial direct current stimulation over the tongue motor cortex reduces appetite in healthy humans. *Brain stimulation*, *13*(4), 1121–1123. https://doi.org/10.1016/j.brs.2020.05.008

Vicario, C. M., Turrini, S., Lucifora, C., Culicetto, L., Ferraioli, F., Falzone, A., et al. (2022). When defeat leaves a bad taste in the mouth: Modulation of tongue corticobulbar output during monetary loss. *Brain Stimulation*, 15, 1448–1450. https://doi.org/10.1016/j.brs.2022.10.010

Wilmskoetter, J., Daniels, S. K., & Miller, A. J. (2020). Cortical and Subcortical Control of Swallowing-Can We Use Information From Lesion Locations to Improve Diagnosis and Treatment for Patients With Stroke?. *American journal of speech-language pathology*, *29*(2S), 1030–1043. https://doi.org/10.1044/2019_AJSLP-19-00068

Witmer, B. G., & Singer, M. J. (1998). Measuring presence in virtual environments: A presence questionnaire. *Presence: Teleoperators and Virtual Environments*, 7, 225–240. https://doi.org/10.1162/105474698565686

Volkow, N. D., Wang, G.-J., & Baler, R. D. (2011). Reward, dopamine and the control of food intake: Implications for obesity. *Trends in Cognitive Sciences*, 15, 37–46. https://doi.org/10.1016/j.tics.2010.11.001

Volkow, N. D., Wise, R. A., & Baler, R. (2017). The dopamine motive system: Implications for drug and food addiction. *Nature Reviews Neuroscience*, 18, 741–752. https://doi.org/10.1038/nrn.2017.130