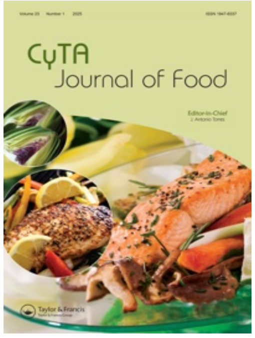

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Bolus viscosity and spoon delivery geometry alter dynamic texture perception of a sweet potato model food and cortical beta oscillations during dual-task swallowing in healthy adults

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ABSTRACT

Swallowing under dual-task conditions requires coordination between oral sensorimotor control and cognitive resource allocation, potentially altering cortical activity even in healthy individuals. This study examined the effects of spoon type and viscosity of pre-gelatinized purple sweet potato on beta-band oscillations during dual-task swallowing. Three viscosity levels (6%, 10.5%, and 18% w/w) were characterized by apparent viscosity and spreadability, while TPA was feasible only for the 18% formulation. Temporal Dominance of Sensations assessed dynamic texture perception. Cortical responses were recorded using electroencephalography, and beta-band event-related desynchronization/synchronization (ERD/ERS) was calculated during a concurrent working memory task. Increased viscosity significantly enhanced mechanical resistance and altered temporal perception. Both viscosity and spoon type significantly affected beta activity, while their interaction was not significant. Lower viscosity produced greater desynchronization, indicating higher sensorimotor demand. These findings demonstrate that food consistency and delivery geometry modulate cortical responses during cognitively demanding swallowing.

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KEYWORDS
Dual-task swallowing; electroencephalography (EEG); purple sweet potato; spoon

Introduction

Swallowing is a coordinated oral–pharyngeal process that depends on precise control of bolus formation, transport, and timing, supported by integrated peripheral and central mechanisms (Cabib et al., 2016). While key elements of swallowing are reflex-driven, the oral phase is strongly influenced by voluntary control and is therefore sensitive to divided attention.

Dual-task studies show that adding a concurrent cognitive demand can modify swallowing performance even in healthy adults (Muhle et al., 2020), highlighting that swallowing competes for shared resources with other ongoing tasks. This framework is useful for revealing subtle changes in oral control that may not be apparent during single-task swallowing.

From a food science and sensory perspective, bolus rheology is a primary determinant of oral processing and is routinely adjusted in dysphagia management to support safer swallowing. Although viscosity modification is clinically relevant, the present study focuses exclusively on cortical and sensory responses during swallowing in healthy adults and does not evaluate swallowing safety outcomes. Increasing viscosity generally slows bolus flow and improves stability, whereas low-viscosity boluses may require greater oral control because they spread and move more rapidly (Prados et al., 2023; Yoon & Yoo, 2016). Despite the widespread use of viscosity modification, fewer studies have examined viscosity as a graded mechanical and sensory load that could influence cortical engagement during swallowing, particularly under cognitively demanding conditions.

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In addition to bolus properties, the manner of delivery may shape early oral handling. Spoon delivery geometry may influence early oral handling (Sasakawa et al., 2021), although direct bolus placement and dispersion were not measured in the present study. These delivery-related differences are expected to influence not only swallowing control but also the time-varying perception of texture attributes during oral processing.

To link food-related factors with physiological responses, beta-band activity measured by electroencephalography (EEG) provides a quantitative index of sensorimotor involvement during voluntary oro-motor actions (Hashimoto et al., 2021). Beta event-related desynchronization/synchronization (ERD/ERS) can capture how sensorimotor demands shift when swallowing is performed alongside a cognitive task, offering a mechanistically relevant readout for oral control under load.

Therefore, this study investigated the independent and combined effects of bolus viscosity and spoon delivery geometry—manipulated via concentration changes in a pre-gelatinized purple sweet potato model food—on swallowing-related beta-band modulation during a dual-task paradigm. In parallel, dynamic texture perception was characterized using Temporal Dominance of Sensations (TDS) to relate changes in physical properties and delivery conditions to perceived oral sensations.

Material and methods

Experimental design

A two-factor factorial design was employed to examine the influence of food viscosity and spoon type on cortical beta activity during dual-task swallowing. Food viscosity was manipulated using three concentrations of pre-gelatinized purple sweet potato flour at 6%, 10.5%, and 18% (w/w) to obtain graded rheological conditions. Spoon type consisted of four geometries: duck spoon, tablespoon, medicine spoon, and pudding spoon. Primary outcomes were rheological, mechanical, and dynamic sensory characteristics of the food. Cortical beta oscillations were evaluated as physiological indicators of sensorimotor demand.

Participants

A total of 10 healthy adults (5 males and 5 females, aged 18–25 years; mean ± SD: 21.3 ± 1.8 years) were recruited from Universitas Brawijaya. All participants provided written informed consent prior to participation in accordance with the approved ethical protocol. All participants were right-handed and had no history of neurological disorders, swallowing impairment, head injury, or use of psychoactive medication. The same individuals participated in both the sensory evaluation (Temporal Dominance of Sensations, TDS) and electroencephalography (EEG) experiments, implementing a within-subject design to reduce inter-individual variability and allow direct comparison between sensory perception and cortical responses. For the sensory study, all 10 participants served as trained panelists and underwent screening procedures including threshold testing, basic taste recognition, and triangle discrimination tests, followed by TDS familiarization training to ensure adequate sensory acuity and task understanding prior to data collection. For the EEG study, the same 10 participants were included, with inclusion criteria consisting of healthy young adults with normal or corrected-to-normal vision and no history of neurological or swallowing disorders, while exclusion criteria included any history of dysphagia, head trauma, cognitive impairment, or use of medication affecting central nervous system function.

Sample preparation

Pre-gelatinized purple sweet potato flour was dispersed in mineral water at the designated concentrations and homogenized until a uniform gel system was formed. The selected concentrations were intended to generate low, intermediate, and high viscosity conditions relevant to oral processing. Samples were prepared fresh and maintained at room temperature prior to testing. Pre-gelatinized flour was used to enable rapid hydration and viscosity development without thermal processing, ensuring consistent rheological properties across batches and minimizing variability related to heating, gelatinization kinetics, and retrogradation (Ulfa et al., 2021). This approach allowed controlled modulation of bolus consistency while maintaining experimental stability during neurophysiological measurements.

Rheological and mechanical characterization

Viscosity

Apparent viscosity was measured using a viscometer (Elcometer 2300 RV) and expressed in centipoise (cP) at a fixed rotational speed of 100 rpm using different spindle geometries selected according to sample consistency (L1 for 6% w/w, L2 for 10.5% w/w, and L4 for 18% w/w formulations). Measurements were conducted at room temperature after sample equilibration, and each formulation was measured in triplicate (Cholakova et al., 2022). Due to the use of different spindle geometries and a fixed rotational speed, the effective shear rate varied between spindle–sample combinations and could only be estimated within instrument-dependent ranges rather than expressed as a single standardized value across all samples. Therefore, the reported values represent apparent viscosity under non-uniform shear conditions rather than absolute viscosity at a defined shear rate.

In addition, the pre-gelatinized sweet potato starch dispersions are expected to exhibit non-Newtonian, shear-thinning behavior, as commonly reported for starch-based systems. However, flow behavior modeling using a power-law approach ($\tau = K \cdot \gamma^{n}$) was not performed due to the single-point measurement design. Consequently, the viscosity values should be interpreted as comparative indicators of relative flow resistance under identical rotational conditions, rather than complete rheological profiles. Therefore, the reported values should not be interpreted as standardized clinical viscosity categories.

Spreadability

Spreadability was evaluated using a bread-based spreading method as a practical proxy to assess large-deformation and surface-spreading behavior of semi-solid samples under low mechanical stress conditions. A fixed amount of sample was placed at the center of a standardized bread substrate and spread using a flat applicator under standardized and consistently applied manual pressure, until no further expansion occurred, after which the maximum spread diameter was recorded (Kılıç et al., 2025). Although this method is not a conventional instrumental rheological technique, it has been previously used in food texture studies as a simple and reproducible approach to characterize spreadability in semi-solid systems, particularly when small-deformation rheometry does not fully capture deformation behavior under oral-like conditions. In the context of dysphagia-oriented food design, spreadability is functionally relevant as it reflects bolus behavior under low-force deformation, where food is distributed across compliant oral surfaces such as the tongue and palate during early oral processing prior to swallowing (Aguayo-Mendoza et al., 2021). Therefore, the bread substrate was used as a simplified and standardized model surface to enable comparative assessment of spreading behavior among formulations, rather than to directly replicate in vivo oral biomechanics. This assay was used as a comparative functional test and should not be interpreted as a validated clinical measure of swallowing safety.

Texture profile analysis

Texture Profile Analysis (TPA) was conducted using a Brookfield CT-3 Texture Analyzer equipped with a TA25/1000 cylindrical probe (25 mm diameter, stainless steel material) to determine hardness, cohesiveness, and adhesiveness. Samples were prepared as $60 \times 60 \times 15$ mm blocks and subjected to a double compression test to 12.5% deformation of the original sample height. The test was performed using a trigger load of 6.8 g, with a pre-test speed of 2 mm/s, a test speed of 5 mm/s, and a return speed of 5 mm/s. Two compression cycles were applied with zero recovery time between cycles using a 1000 g load cell. Data were collected at 50 points per second. For the 18% formulation, TPA measurements were performed in duplicate ($n = 2$). The selected instrumental parameters were designed to simulate oral compressive deformation during mastication, particularly the repeated mechanical breakdown of semi-solid bolus structures in the oral cavity (Nishinari et al., 2019).

Texture Profile Analysis (TPA) was conducted exclusively on the 18% w/w formulation, as this concentration possessed sufficient structural integrity to undergo dual compression cycles. The 6% and 10.5% w/w samples exhibited low-viscosity, fluid-like flow behavior that precluded the acquisition of reliable and meaningful TPA parameters under the selected testing conditions. Because TPA was conducted only for the 18% formulation in duplicate ($n = 2$), these measurements were interpreted descriptively and should not be considered definitive estimates of mechanical properties across formulations. For these lower concentrations, mechanical characterization was instead provided through apparent viscosity and spreadability measurements, which are more appropriate for fluid and semi-fluid systems commonly investigated in dysphagia-oriented food research. While the absence of equivalent TPA measurements across all formulations limits direct comparison of mechanical properties, the significant differences observed in viscosity and spreadability ($p < 0.05$) nevertheless provide a physical basis for the distinct textural perceptions (e.g. "thin" versus "thick") identified in the TDS results. However, additional unmeasured properties, such as transient cohesiveness or deformation behavior during oral processing, may also have contributed to the observed neurophysiological responses.

Dynamic sensory evaluation

Temporal Dominance of Sensations (TDS) was applied to characterize dynamic texture perception during oral processing. Ten trained panelists aged 18–25 years participated in the evaluation following sensory screening and familiarization procedures. Panelists underwent structured training sessions (approximately 2 sessions) involving an introduction to TDS methodology, attribute familiarization, and practice using the SensoMaker v1.95 platform to ensure task comprehension and response consistency prior to formal data collection. Samples were presented at a fixed volume of 3 mL at room temperature. The TDS evaluation focused specifically on the three bolus formulations (6%, 10.5%, and 18% w/w) to establish their sensory profiles independent of the mechanical delivery factors. Each participant evaluated each sample in three independent replicates, resulting in 9 total TDS trials per panelist, presented in a randomized and counterbalanced order to minimize order effects.

During each 40 s evaluation period, panelists continuously selected the dominant sensory attribute perceived over time (Isac-Torrente et al., 2023). Evaluated attributes included thin, mid-thick, thick, grainy, smooth, and adhesive. Panelists were instructed to consume the entire sample in a single oral intake. Swallowing was allowed to occur naturally during the evaluation period, and panelists continued reporting perceived sensations after swallowing to capture both oral-phase and post-swallow (aftertaste/residual) dynamics within the 40 s window. This protocol ensured that transitions from oral processing to post-swallow perception could be recorded without interrupting the temporal continuity of sensation. Dominance Rate maximum (DRmax) and Time to maximum dominance (Tmax) were calculated to characterize the temporal evolution of sensory perception.

Electroencephalography during dual-task swallowing

Electroencephalography (EEG) recordings were conducted using a portable multi-channel headset positioned according to the International 10–20 system Emotiv EPOC X. Analysis focused on the fronto-central channels FC5 and FC6, selected to represent scalp regions overlying sensorimotor cortical areas involved in voluntary swallowing control (Ren et al., 2023). Thus, FC5 and FC6 were used as targeted fronto-central indicators rather than as a complete topographical representation of swallowing-related cortical activity. Channels FC5 and FC6 were specifically selected for analysis because they are strategically positioned over the frontocentral regions, including the premotor cortex and the inferior frontal gyrus. These areas serve as key nodes for the planning and execution of oropharyngeal movements and are highly sensitive to cognitive load during dual-task scenarios (Suntrup et al., 2014). While the portable EEG montage focused on these sites to observe the interface between motor and executive control, the exclusion of other channels (e.g. C3, C4, Fz) is acknowledged as a limitation in providing a broader map of the distributed swallowing network.

The device was securely fitted on the participant's head to maintain stable electrode contact throughout the experimental session (Figure 1a). Signal quality was monitored prior to recording using the EmotivPRO interface, and only channels displaying stable contact quality indicators (manufacturer-defined optimal contact status, indicated as "green") were included for analysis (Figure 1b) (Liu et al., 2025). Raw EEG signals were visually inspected prior to preprocessing to identify segments containing excessive noise or instability.

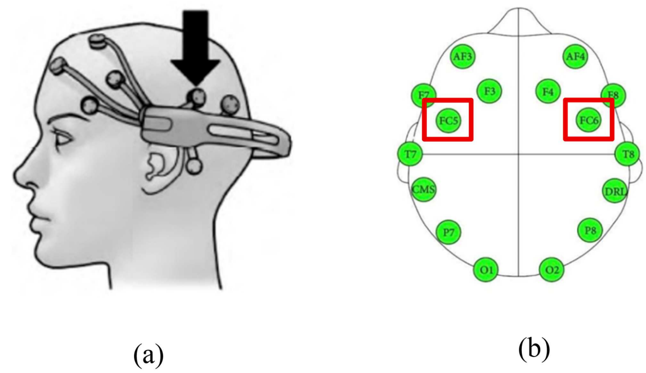


Figure 1. EEG recording configuration used during dual-task swallowing. (a) Placement of the portable EEG headset on the participant's head during data acquisition. (b) Electrode layout based on the international 10–20 system; frontocentral channels (FC5 and FC6) were selected for beta-band analysis.

Artifacts including eye blinks, ocular movements, muscle activity, and abrupt signal fluctuations were removed using manual epoch rejection. Artifact-contaminated epochs were excluded by visual inspection; however, the exact number and proportion of rejected epochs were not logged. No participant was excluded. This is acknowledged as a methodological limitation. Signals were band-pass filtered (12–16 Hz) to isolate beta-low frequency activity. No participants were excluded due to poor signal quality; however, artifact-contaminated epochs were excluded from further analysis. Swallow onset was defined based on a time-locked experimental protocol (~180 s) during assisted feeding and was verified through direct behavioral observation by the experimenter. EEG segmentation was synchronized to this predefined event timing. No EMG or audio-based physiological swallow markers were available; therefore, temporal alignment represents a behavioral-event-based estimate rather than a physiological onset detection method.

This study was conducted following approval from the Institutional Ethics Committee of Universitas Negeri Malang No.17.11.12/UN32.14.2.8/LT/2025. Participants performed swallowing under dual-task conditions to induce cognitive–motor interference, as attentional load has been shown to modulate swallowing performance even in healthy individuals (Krishnamurthy et al., 2021; Muhle et al., 2020). Food samples were delivered using four spoon types to represent variations in delivery geometry. Spoon shape and bowl curvature have been reported to influence lip seal efficiency and bolus control during oral processing (Sasakawa et al., 2021). To isolate the mechanical contribution of spoon geometry, bolus volume was standardized at 3 mL across all conditions (Figure 2a–d).

EEG signals were continuously recorded throughout each trial and segmented according to the structured experimental timeline, which consisted of a resting baseline period, a dual-task reading phase, and a swallowing event performed under cognitive load. The baseline interval (90–105 s) was recorded while participants fixated on a visual marker without additional tasks and served as the reference (R) for ERD/ERS computation. The dual-task reading phase occurred between 135 and 165 s, participants performed silent reading of a factual text (80–120 words) and were instructed to memorize the details during the subsequent 15-s retention interval to maintain cognitive load. At the 180 s mark, the swallowing phase was initiated via an assisted feeding protocol, where the researcher directly administered the 3 mL sample into the participant's oral cavity using the designated spoon geometry. This procedure was strictly implemented to eliminate upper-limb motion artifacts that could compromise the integrity of the cortical signal. Immediately following the swallow, participants were required to provide a verbal response to a comprehension question to verify active cognitive engagement throughout the experiment. Behavioral performance during the dual-task condition showed a mean comprehension accuracy of 83.33%, indicating that participants consistently engaged with the reading task while performing swallowing. Comprehension accuracy confirmed task engagement; however, the absence of reaction-time data limited quantitative assessment of dual-task interference. Although this suggests successful task engagement, the moderate accuracy level implies that cognitive load was maintained without reaching a ceiling effect.

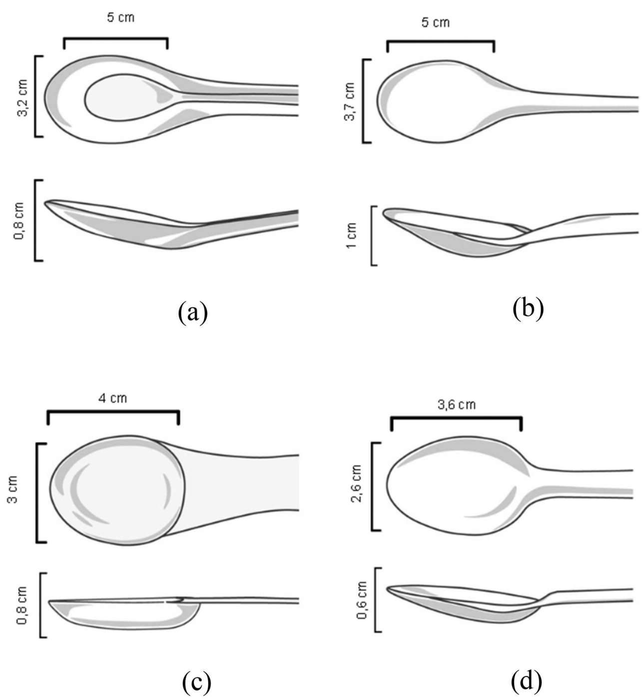


Figure 2. Dimensions and geometrical characteristics of the four spoon types used in the study: (a) duck spoon, (b) table spoon, (c) medicine spoon, and (d) pudding spoon. A standardized bolus volume of 3 mL was used for all spoon conditions.

Beta-low spectral power (12–16 Hz) was extracted from the baseline interval and from a short window centered around the instructed swallowing time point. Event-related desynchronization/synchronization (ERD/ERS) percentages were calculated using the following equation:

$$\mathrm{ERD/ERS}\,(\%) = \frac{A - R}{R} \times 100\%, \tag{1}$$

where A represents beta power during the swallowing interval and R represents baseline beta power. Negative values indicate relative desynchronization, whereas positive values indicate synchronization (Silva et al., 2018). EEG signals were visually inspected prior to analysis to ensure acceptable electrode contact quality. Raw EEG signals were filtered using a (12–16 Hz) band-pass filter, and epochs containing excessive movement, eye blinks, or muscle artifacts were excluded based on visual inspection during preprocessing. Signals were segmented according to the experimental timeline. The baseline interval (R) corresponded to 90–105 s, whereas the swallowing interval (A) was defined as a 5 s window centered around the instructed swallow event (~180 s). Spectral power in the beta-low band (12–16 Hz) was extracted from both intervals and normalized relative to baseline according to the ERD/ERS equation.

Statistical analysis

Rheological, mechanical, and sensory parameters were analyzed using one-way Analysis of Variance (ANOVA) to evaluate the effect of viscosity level. When significant main effects were detected, pairwise comparisons were performed using Tukey's Honestly Significant Difference (HSD) post hoc test. EEG ERD/ERS data were analyzed using a linear mixed-effects model to account for the repeated-measures design. The LME model included pre-gelatinized purple sweet potato flour concentration, spoon type, and EEG channel (FC5 and FC6) as fixed effects. The model tested a two-way interaction between concentration and spoon type. Participant was included as a random intercept to account for repeated measures. EEG channel effects were evaluated as a within-subject fixed factor. No interaction terms involving EEG channel were modeled; channel was included only to assess potential lateral differences between FC5 and FC6. Statistical significance was established at a 95% confidence level ($\alpha = 0.05$), all performed using Minitab 22 (Minitab

LLC, State College, PA, U.S.A). Trial order was not modeled as a covariate because all measurements were conducted in a single session and condition presentation was randomized and counterbalanced.

Results

Physical characteristics of pre-gelatinized purple sweet potato

Spreadability and viscosity test

As presented in Table 1, flour concentration significantly affected both spreadability and viscosity ($p < 0.05$). Spreadability increased from 2.13 ± 0.15 cm (6% w/w) to 4.90 ± 0.30 cm (18% w/w), with 18% significantly different from the lower concentrations. Viscosity increased progressively across concentrations, from 31.0 ± 2.65 cP (6% w/w) to 148.7 ± 1.53 cP (10.5% w/w) and 2606.7 ± 5.77 cP (18% w/w). All concentrations differed significantly from one another ($p < 0.05$), confirming clear rheological separation.

Texture profile analysis (TPA)

Because lower concentrations lacked structural integrity under compression, TPA was conducted only for the 18% (w/w) sample. These TPA values should be interpreted descriptively because measurements were performed only for the 18% formulation in duplicate ($n = 2$). As shown in Table 2, hardness was 369.83 ± 94.43 g, cohesiveness 0.74 ± 0.17, and adhesiveness 7.3 ± 1.58 mJ, indicating a structured semi-solid gel capable of maintaining form under mechanical load.

Temporal dominance of sensation

The effect of concentration on temporal sensory attributes is summarized in Table 3. Concentration significantly influenced viscosity-related attributes (thin, mid-thick, and thick) for both DRmax and Tmax ($p < 0.05$), whereas grainy, smooth, and adhesive attributes were not significantly affected ($p > 0.05$).

Table 1. Apparent viscosity and spreadability of pre-gelatinized purple sweet potato formulations.

Pre-gelatinized purple sweet potato flour concentration (w/w)	Spreadability (cm), mean ± SD	Viscosity (cP) (mean ± SD)
6%	2.13 ± 0.15^{b}	31 ± 2.65^{c}
10.5%	2.63 ± 0.55^{b}	148.7 ± 1.53^{b}
18%	4.90 ± 0.30^{a}	2606.7 ± 5.77^{a}

Values with different superscript letters are significantly different according to Tukey's HSD post hoc test ($p < 0.05$).

Table 2. Texture profile analysis results for the 18% (w/w) pre-gelatinized purple sweet potato formulation.

Parameter	Mean ± SD	Unit
Hardness	369.83 ± 94.43	g
Cohesiveness	0.74 ± 0.17	–
Adhesiveness	7.3 ± 1.58	mJ

Table 3. Effect of concentration on TDS attributes.

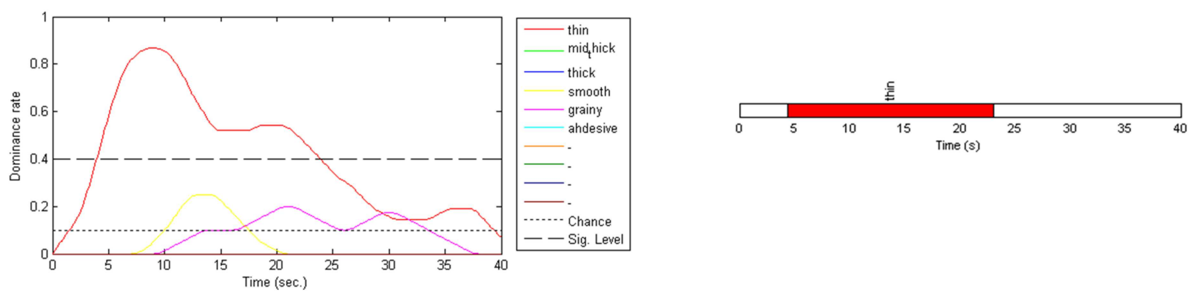
	p-value	
Attribute	DRmax	Tmax
Thin	0.000^{a}	0.017^{a}
Mid-Thick	0.000^{a}	0.007^{a}
Thick	0.000^{a}	0.001^{a}
Grainy	0.589	0.726
Smooth	0.290	0.764
Adhesive	0.092	0.208

[a]Indicates significant effect ($p < 0.05$).

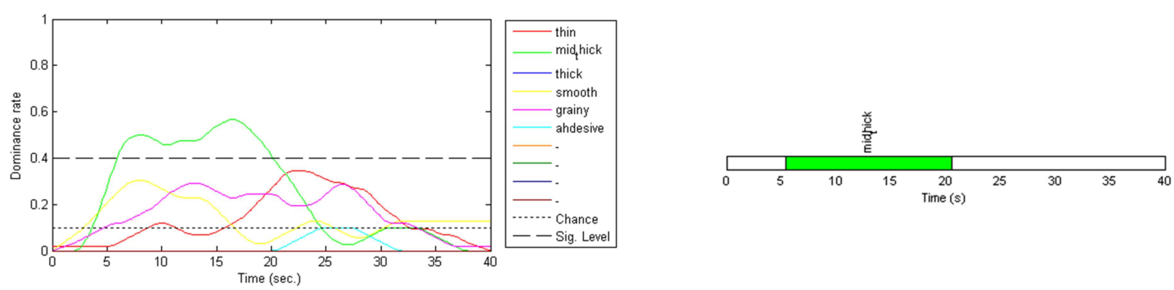
As illustrated in Figure 3a–c, the 6% (w/w) formulation exhibited the highest dominance of thin perception, 10.5% (w/w) showed peak mid-thick dominance, and 18% (w/w) demonstrated dominant thick perception. These results confirm perceptual differentiation among the three formulations.

Electroencephalography (EEG) test results

A representative beta-low (12–16 Hz) power trace at FC5 is shown in Figure 4. This figure is provided for illustrative purposes only, whereas group-level effects were evaluated using the linear mixed-effects model and post hoc analyses reported in Tables 4–6. EEG channel (FC5 vs FC6) was included as a within-subject fixed factor in the LME model to assess potential lateral differences in beta activity (Table 4). However, no significant main effect of the channel was observed ($p = 0.978$), indicating comparable responses between FC5 and FC6 under the current experimental conditions. Post hoc comparisons (Tables 5 and 6) indicated that 6% (w/w) differed significantly from 10.5% and 18% (w/w), and that the medicine spoon differed significantly from the duck spoon.



(a)



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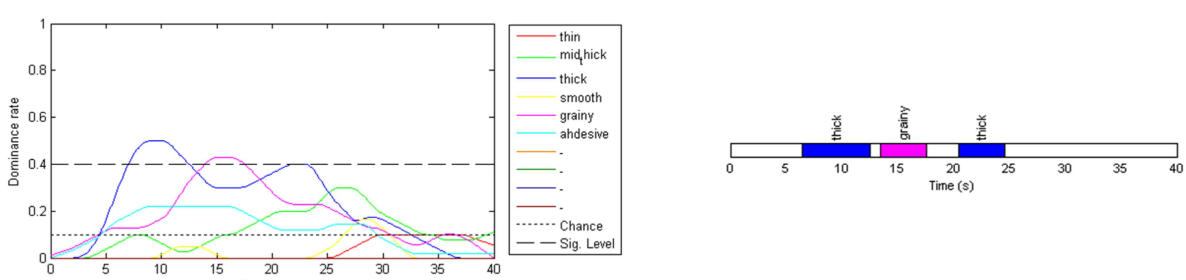

(c)

Figure 3. Temporal dominance of sensation graph of pre-gelatinized purple sweet potato flour concentration at (a) 6%, (b) 10.5%, and (c) 18% (w/w).

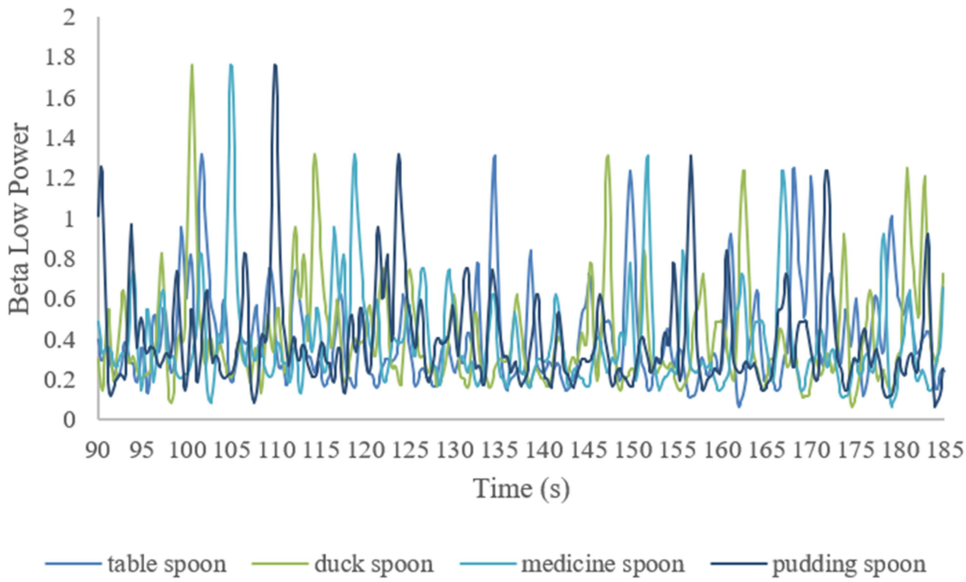

Figure 4. Representative beta-low band power (12–16 Hz) recorded at FC5 during dual-task swallowing at 10.5% (w/w) pre-gelatinized purple sweet potato concentration in a single participant. The displayed time segment (90–185 s) includes the baseline interval (90–105 s), the dual-task reading phase (135–165 s), and the swallow onset (~180 s) used for ERD/ERS computation.

Table 4. Results of the mixed-effects model analysis.

Source of Variation	p-value
Pre-gelatinized purple sweet potato flour concentration	0.005*
Spoon type	0.019*
Channel (FC5–FC6)	0.978
Pre-gelatinized purple sweet potato flour concentration * spoon type	0.577

[*] Indicates a significant effect (p-value < 0.05). The model included concentration, spoon type, and EEG channel as fixed effects, participant as a random intercept, and only the concentration × spoon type interaction.

Table 5. Results of the post hoc test for pre-gelatinized purple sweet potato flour concentration.

Concentration of pre-gelatinized purple sweet potato flour (w/w)	%ERD/ERS (mean ± SD)
6%	-7.77 ± 37.67^{b}
10.5%	8.74 ± 38.58^{a}
18%	2.63 ± 43.48^{a}

Values with different superscript letters are significantly different according to Tukey's HSD post hoc test ($p < 0.05$). Negative values indicate ERD; positive values indicate ERS. Pairwise Cohen's d effect sizes are reported in the Discussion.

Table 6. Results of the post hoc test for spoon type.

Spoon type	%ERD/ERS (mean ± SD)
Duck	-6.58 ± 38.12^{b}
Table	1.80 ± 47.52^{ab}
Medicine	11.43 ± 53.78^{a}
Pudding	-1.84 ± 48.65^{ab}

Values with different superscript letters are significantly different according to Tukey's HSD post hoc test ($p < 0.05$). Negative values indicate ERD; positive values indicate ERS. Pairwise Cohen's d effect sizes are reported in the Discussion.

Discussion

Physical characteristics of pre-gelatinized purple sweet potato

Rheological characterization demonstrated a clear concentration-dependent increase in internal resistance. As shown in Table 1, viscosity increased markedly from 31 cP at 6% (w/w) to 148.7 cP at 10.5% (w/w) and 2606.7 cP at 18% (w/w), reflecting progressive gel network formation typical of pre-gelatinized starch systems (Gong et al., 2024; Liu et al., 2017). Spreadability results (Table 1) further indicated that the 18% formulation exhibited significantly greater deformation capacity. Although higher viscosity is generally associated with reduced flow, concentrated pre-gelatinized starch systems may exhibit viscoelastic and deformation-resistant behavior that enables cohesive spreading under applied force without immediate structural breakdown (Lowithun & Sagis, 2024). This behavior was supported by Texture Profile Analysis results (Table 2), where measurable hardness and cohesiveness confirmed the formation of a structurally integrated semi-solid matrix (Nishinari et al., 2019). Thus, increasing concentration modified not only flow resistance but also bolus integrity and deformation mechanics relevant to oral processing.

Dynamic sensory perception

Mechanical transitions were directly reflected in temporal sensory perception. As summarized in Table 3 and illustrated in Figure 3a–c, concentration significantly affected viscosity-related attributes. The 6% (w/w) formulation showed dominant *thin* perception (Figure 3a), consistent with its low viscosity and weak structural cohesion (Table 1). In contrast, the 18% (w/w) formulation demonstrated dominant *thick* perception (Figure 3c), indicating immediate resistance upon oral contact. The 10.5% (w/w) formulation exhibited peak *mid-thick* dominance (Figure 3b), suggesting an intermediate structural state in which gel formation was sufficient to provide cohesion but remained deformable. These findings align with evidence that rheological structure governs dynamic oral perception during breakdown and bolus formation (Lavergne et al., 2017; Nguyen et al., 2018). Importantly, the sensory data confirm that the three concentrations produced distinct perceptual states rather than simple incremental thickening, validating their use as differentiated mechanical conditions for neurophysiological testing.

EEG beta-low responses under dual-task conditions

Neurophysiological modulation paralleled the physical and sensory findings. As shown in Table 5, the 6% (w/w) condition elicited significant beta desynchronization compared with both 10.5% and 18% (w/w). Effect size analysis for post hoc comparisons of pre-gelatinized purple sweet potato flour concentration indicated generally small differences in %ERD/ERS responses. The comparison between 10.5% and 6% (w/w) showed a small to moderate effect (Cohen's $d \approx 0.43$), while the difference between 18% and 6% (w/w) was smaller ($d \approx 0.26$). The comparison between 10.5% and 18% (w/w) showed a very small effect ($d \approx 0.15$). Overall, these results suggest that although some statistically significant differences were observed, the magnitude of the effects was generally small. Taken together, these findings should be interpreted as exploratory and indicate limited and variable modulation of %ERD/ERS responses in healthy participants, with substantial inter-individual variability reflected in the large standard deviations across conditions. The representative beta-low trace in Figure 4 illustrates event-related modulation around swallow onset. Beta desynchronization over fronto-central regions has been associated with increased sensorimotor recruitment during voluntary motor execution (Cuellar et al., 2016; Hashimoto et al., 2021). Given its low viscosity and dominant thin perception, the 6% (w/w) formulation likely required greater voluntary stabilization and timing precision under dual-task conditions, increasing cortical demand.

In contrast, both 10.5% and 18% (w/w) showed relative beta synchronization and did not differ significantly. Although 18% (w/w) exhibited substantially higher viscosity (Table 1), it did not induce stronger desynchronization than 6% (w/w). This suggests that cortical demand does not increase linearly with viscosity. Rather, once sufficient structural stability is achieved, additional mechanical resistance does not proportionally elevate cortical recruitment in healthy adults. In contrast to the 6% (w/w) condition, both the 10.5% and 18% (w/w) formulations elicited relative beta synchronization (ERS) and did not differ significantly from each other (Table 5), whereas both differed significantly from the 6% (w/w) condition, which showed beta desynchronization (ERD). These results indicate that ERS was observed under the higher-viscosity conditions (10.5% and 18%), while ERD was observed in the lowest-viscosity condition (6%). The relatively large standard deviations observed across conditions suggest substantial inter-individual variability in cortical responses during swallowing under dual-task conditions, indicating heterogeneous sensorimotor adaptation strategies among participants (Babiloni et al., 2017).

Influence of spoon geometry

Spoon type significantly influenced cortical responses, with the medicine spoon producing greater synchronization than the duck spoon. As shown in Table 6, effect size analysis for spoon type comparisons showed generally small differences in %ERD/ERS responses. The medicine spoon showed higher beta synchronization than the duck spoon, although the effect size was small to moderate. The largest effect was observed between Duck and Medicine spoon types (Cohen's $d \approx 0.39$), indicating a small to moderate effect. Other comparisons showed small to negligible effects, including Duck vs Table ($d \approx 0.19$), Duck vs Pudding ($d \approx 0.11$), Table vs Medicine ($d \approx 0.19$), Table vs Pudding ($d \approx 0.08$), and Medicine vs Pudding ($d \approx 0.26$). These findings indicate that although some spoon type comparisons reached statistical significance in post hoc testing, the magnitude of differences was generally small. This suggests that spoon geometry may influence %ERD/ERS responses only modestly under the present experimental conditions, and that inter-individual variability plays a substantial role in the observed outcomes.

The four spoon types were selected to represent distinct delivery geometries and are shown in Figure 2. However, quantitative geometric parameters such as bowl depth, curvature radius, and lip contact angle were not directly measured. Therefore, spoon classification was based on observable functional design differences commonly used in food administration contexts. Although previous studies have reported that spoon geometry may influence lip sealing efficiency and bolus transport behavior (Sasakawa et al., 2021), no direct measurements or imaging of bolus dispersion were performed in this study. Accordingly, interpretations regarding spatial bolus distribution (e.g. centralized versus dispersed placement) cannot be substantiated and should be considered hypothetical. Future work should incorporate geometric profiling and imaging-based analysis (e.g. high-speed videography or intraoral tracking) to objectively evaluate bolus placement and transport dynamics.

Study limitation

This study has several limitations that should be considered when interpreting the findings. First, the experiments were conducted exclusively in healthy young adults; therefore, the results cannot be directly generalized to dysphagic populations. Swallowing safety outcomes such as penetration or aspiration risk were not assessed, limiting the ability to draw clinical conclusions regarding dysphagia management. Second, EEG analysis was restricted to two fronto-central channels (FC5 and FC6), which does not capture the full spatial dynamics of the swallowing-related cortical network, such as contributions from C3, C4, or Fz regions. Third, although artifact-contaminated EEG epochs were excluded during preprocessing, the exact number and proportion of rejected epochs were not logged. Consequently, detailed evaluation of artifact-rejection efficiency was not possible and should be considered a methodological limitation. Fourth, texture profile analysis could not be applied uniformly across all viscosity levels due to the fluid-like nature of the lower-concentration samples, resulting in partial mechanical characterization. Finally, although behavioral measures indicated task engagement, additional metrics such as reaction time were not recorded, limiting a more detailed quantification of cognitive load during dual-task performance. Future research should address these limitations by including clinical populations, employing high-density EEG, and integrating more comprehensive behavioral and biomechanical assessments to better characterize the relationship between food properties, neural responses, and swallowing function.

Conclusion

This study demonstrates that bolus viscosity (manipulated via pre-gelatinized purple sweet potato flour concentration) and spoon delivery geometry independently modulate low-beta cortical activity (ERD/ERS) during dual-task swallowing in healthy adults, as measured using EEG at fronto-central channels (FC5 and FC6). The low-viscosity condition (6% w/w) elicited greater beta ERD compared to the higher viscosity conditions, indicating higher relative sensorimotor demand. In contrast, both 10.5% and 18% (w/w) conditions elicited beta ERS and did not differ significantly from each other, while both differed significantly from the 6% condition. Therefore, no superiority or optimality can be attributed to either the 10.5% or 18% formulation based on %ERD/ERS outcomes in this study. Spoon geometry also influenced cortical activity, with the medicine spoon showing significantly higher beta synchronization compared to the duck spoon, although effect sizes were generally small across comparisons. No significant interaction between viscosity and spoon type was observed, suggesting independent contributions of both factors to cortical modulation during swallowing under cognitive load. Overall, these findings indicate that swallowing-related cortical responses are modulated by bolus structure and delivery geometry, with modest effect sizes and substantial inter-individual variability in healthy adults. From an applied perspective, these findings suggest that both food rheology and delivery geometry may influence oral processing and cortical demand in healthy individuals. However, translation to dysphagia-oriented food design should be made cautiously. Clinical validation in individuals with dysphagia is required before any safety-related or dietary recommendations can be made, as swallowing safety outcomes were not evaluated and clinical validation in dysphagic populations is still required.

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Author contributions

CRediT: **Kiki Fibrianto:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Project administration, Supervision, Validation, Writing – review & editing; **Angelica Pasha Dievia:** Formal analysis, Investigation, Software, Visualization, Writing – original draft; **Widya Dwi Rukmi Putri:** Funding acquisition, Methodology, Supervision; **Gleb Yakubov:** Conceptualization, Resources.

Disclosure statement

The authors declare no potential conflict of interest.

Data availability statement

Data supporting the findings of this study are available from the corresponding author upon reasonable request. The dataset includes anonymized EEG recordings (FC5 and FC6 channels), behavioral performance data, rheological measurements, and Temporal Dominance of Sensations (TDS) outputs. Due to ethical considerations and participant consent restrictions, raw identifiable data cannot be publicly shared. Preprocessing scripts are available upon request; however, historical logs of rejected epoch counts were not retained.

Declaration of AI-assisted editing and reference management

During manuscript preparation, the authors used QuillBot to support language refinement, including paraphrasing, grammar correction, and readability improvement. Mendeley was used solely to manage references and generate the citation list. Neither tool was used to generate research data, perform analyses, manipulate results, or derive scientific conclusions. All text was critically reviewed, revised as needed, and approved by the authors, who assume full responsibility for the manuscript's integrity, originality, and compliance with publication ethics.

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