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Effects of Tactile Stimulation by Foams of Different Viscosities on Electroencephalogram Signals From Brain Regions Involved in Emotional Processing

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Synopsis

Objective evaluation of the influence of foam-induced tactile stimulation on participants' emotions is important. This study aimed to quantify neurophysiological indices of the emotional effect of tactile stimulation by foam of different viscosities. Twelve healthy adult females were asked to wash their faces with three types of facial cleansing foams of low, medium, or high viscosity while electroencephalograms of their brain activities were recorded. Salivary cortisol levels were measured before and after face-washing. Foam-mediated tactile stimulation during face-washing increased activity in the orbitofrontal and anterior cingulate cortex. However, the increase in both regions was significantly smaller with the use of high viscosity foam than that with other foam types. With low viscosity foam, the neural activity was significantly higher when the foam was placed on participants' faces compared to on their hands. Furthermore, the neural activity hemisphericity and the extent of changes in salivary cortisol levels during face-washing indicated that the high viscosity foam elicited more negative emotions than the low viscosity foams. The results suggest that tactile stimulation with foam causes emotional changes in participants according to foam viscosity, with low and medium viscosity foams causing pleasing sensations and high viscosity foams causing distinctly stressful emotions.

INTRODUCTION

During somatosensation, signals are generated on the dermal surface by touch stimuli. These signals are then transmitted to the central nervous system via peripheral nerves and are processed by neural networks.[1] Through a wide range of tactile receptors located on the surface of our bodies, we constantly receive and process information from the external world. Tactile information can cause a myriad of emotional stimulations.[2] For example, touching smooth or soft objects often elicits a sense of comfort.[3] Studies suggest that the role of tactile information in creating pleasant emotions may be important in designing and developing appropriate stimuli to elicit emotional responses.[4]

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Somatosensation plays a central role in human physiology,[1] psychology,[5] and biomedical engineering.[6,7] Related research findings have wide application in the rehabilitation field, in innovations in electronic skin and artificial limbs, and in quality assessment of comfort in apparel and cosmetics. Yasasaka *et al.* used three tactile objects with plastic, cloth, and sandpaper surface materials and reported that differences in the features of the surface materials were associated with differences in affectivity, cognitive processes, and perceived vividness/familiarity.[8] Kida and Shinohara examined the effects of tactile stimuli on participants' emotions using wood, velvet, and a paintbrush.[9] Gentle stroking with a soft velvet cloth produced the highest pleasantness ratings and the emotion was accompanied by activity in the frontal polar and orbitofrontal cortex (OFC). Greco *et al.* reported that the activity of alpha and beta frequency bands in the contralateral prefrontal and median cerebral cortex accompanied pleasant sensations of tactile stimulation.[10]

However, only a few reports have been published on the emotional response to foam-mediated tactile stimulation. We wash our faces and hands daily and repeatedly experience the foamy sensation of facial cleansers and hand soap on our faces and hands. Improving the emotional evaluation of washing with foam is important to provide a pleasant feeling, and will thereby promote hygiene education. Given that the qualities and properties of foam in facial cleansers and hand soaps can be adjusted by modifying the types and quantities of ingredients, the optimal quality of foam that provides comfort and ease of use has been examined. In recent years, research has focused on foam viscosity.[11] It has been reported that a lower viscosity results in a finer foam. However, Ohmura *et al.* evaluated the perceived quality of foam using only subjective questionnaires.[11] Objective evaluation of the influence of foam-induced tactile stimulation on participants' emotions is an important next step.

This study aimed to examine the emotional effect of tactile stimulation by foam with different viscosities through the recording of electroencephalogram (EEG) signals and salivary cortisol levels during the facial cleansing process. We hypothesized that a lower foam viscosity would generate more pleasant emotions, which should be reflected in neurophysiological parameters.

METHODS

PARTICIPANTS

We included 12 healthy female adults (mean age: 20.2 ± 0.7 years) with no history of orthopedic or neurological diseases. The sample size was determined based on previous studies[12,13] that conducted spatial analyses of neural activity during stimuli that elicit emotional changes, like those expected in the present study. This study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Review Committee of Kyoto Tachibana University (Approval No. 19-38). This study's purpose, contents, and procedures were explained to the participants orally and in writing, and informed consent was obtained.

SELECTIONS OF EXPERIMENTAL SAMPLES

Three types of facial cleansers with different levels of viscosity were used as samples to assess the tactile effect of foam on participants' emotions. The cleansers were unscented and colorless. We evaluated the foam viscosity of 12 different types of facial cleansers on a 7-point scale (0 = low to 6 = high), and from these products three foam samples were selected: sample A: low viscosity; sample B: medium viscosity; and sample C: high viscosity. In addition, the viscoelasticities of the three foam samples were objectively measured using a HAAKE RheoStress 600 (Thermo Fisher Scientific, Waltham, MA, USA). The analysis conditions were as follows: double cone plate (diameter: 60mm; angle: 1°); shear rate: 100 s^{-1}; measurement temperature: 25 °C; and measurement time: 120 seconds; each sample was measured twice. The foam samples used were prepared by the same researcher immediately before the measurement procedure by weighing 2g of facial cleanser in a milk frother, adding 24mL of water, and frothing the foam with 50 up-and-down movements. The results of the viscosity measurements are shown in Table I. The magnitude relation of viscosity measurements of the three samples was consistent with the results of the 7-point sensory evaluations previously performed by the researcher.

Table I
Viscosity of Foam Samples

Viscosity (Pa·s)	Sample A	Sample B	Sample C
First measurement	0.162	0.319	0.418
Second measurement	0.181	0.328	0.412
Mean	0.172	0.324	0.415

EXPERIMENTAL PROCEDURE

Figure 1 illustrates the experimental procedure. First, the participants were instructed to rest in a sitting position with their eyes open for 120 seconds. Then, a foam sample prepared by a researcher was placed on the participants' palms and they felt the foam on their hands for 30 seconds (phase 1). They then used their hands to apply the foam to their cheeks and experienced the sensation on their faces for 3 seconds (phase 2). The participants then spread the foam on their faces, washed off the cleanser with water, and dried the water from their faces and hands with a paper towel; there was no time limit set for this part of the procedure. This facial cleansing procedure was performed using the three different foam samples selected for this study. The sample order was randomized for each participant to control the order effect, and sufficient resting time (10 to 15 minutes) was provided between the applications of samples in consideration of the after-effect of the tactile stimulus. The foam samples were prepared using the same procedure as that used to measure viscosity, and the amount and quality of foam were standardized across participants and between treatments.

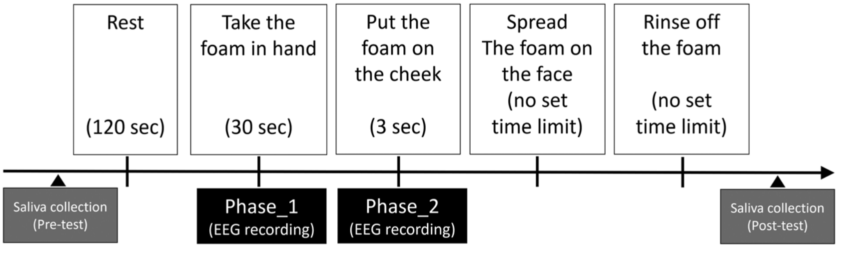

Figure 1. Experimental protocol of the facial cleansing procedure.

EEG MEASUREMENT AND ANALYSIS

We measured the EEG signals during phases 1 and 2 using active electrodes (g.tec medical engineering GmbH, Schiedlberg, Austria) and a Livo bio-signal analysis system (Tec-Gihan, Kyoto, Japan) for the tests. The measurements were derived from 15 sites (Fpz, Fz, Cz, Pz, Oz, F3, F4, C3, C4, P3, P4, F7, F8, T7, T8) using both earlobes as reference electrodes, according to the international 10-20 EEG system. Data were filtered with a bandpass of 1–30 Hz, and the sampling frequency was 1,000 Hz. During the task, motor and sensory processing neural activities related to hand movement control and facial sensory input information were superimposed with additional emotional responses to the textural stimuli. We extracted EEG activities during hand movements in a period equivalent to the task execution time and when only the hand touched the face. Those activities were subtracted from the EEG activity during the task. Subtracted data (for example, EEG data capturing emotional responses) were then normalized. EEG data were analyzed using the standardized low-resolution brain electromagnetic tomography brain function imaging filter,[14] and the areas and values of the neural activity ($\mu A/mm^2$) were calculated. In phase 1, the 30 seconds of EEG data were separated into 3 second epochs, and the mean signal for each epoch was used. The data for phase 2 (total duration 3 seconds) were used without modification.

SALIVARY CORTISOL MEASUREMENT

Saliva samples were collected and the salivary cortisol levels were measured before and after the facial cleansing procedure (Figure 1). The samples were collected using the SOMA Oral Fluid Collector (SOMA Bioscience, Wallingford, UK). An oral fluid collector swab was placed on the participant's tongue and left in place with the mouth closed. When 0.5 mL of saliva was absorbed, the swab was removed from the participant's mouth and stored in 3 mL of buffer solution. The samples were then analyzed using a SOMA lateral flow device (LFD; SOMA Bioscience, Wallingford, UK) and a SOMA cube reader (SOMA Bioscience, Wallingford, UK).

STATISTICAL ANALYSIS

We used the exact low-resolution brain electromagnetic tomography (eLORETA) SnPM 26 package (multiple paired t-tests with nonparametric randomization[15]) to investigate the neural sites activated by the foam-induced tactile stimulation during face-washing (phases 1 and 2). In the eLORETA analysis, regions of significant neural activity were colored and plotted. A two-way analysis of variance (ANOVA) was used to compare neural activities by phase (two groups) and by sample (three groups), and the salivary cortisol levels by collection time (two groups) and by sample (three groups). A one-way ANOVA with a Bonferroni post hoc analysis was used to compare the salivary cortisol changes by sample between groups. The significance level was set at 5%, and all analyses were performed using SPSS Statistics version 26.0 (IBM, Armonk, NY, USA).

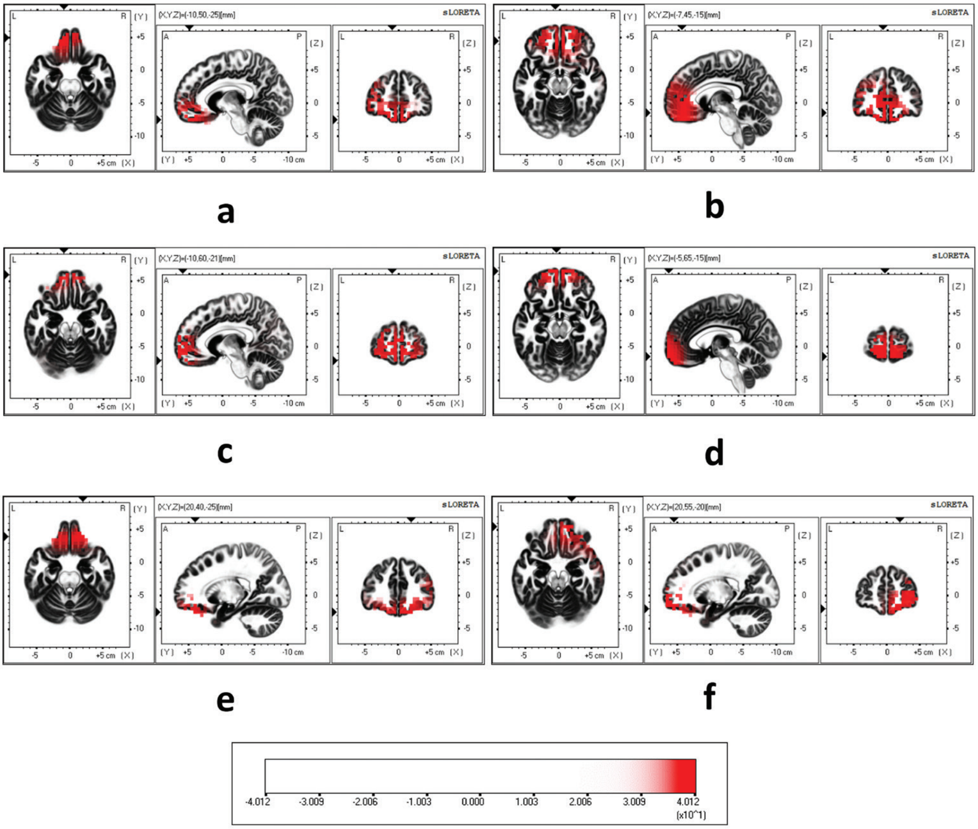

Figure 2. Regions with increased neural activity indicating the reward system response to tactile stimuli: **(a)** phase 1 – sample A; **(b)** phase 2 – sample A; **(c)** phase 1 – sample B; **(d)** phase 2 – sample B; **(e)** phase 1 – sample C; and **(f)** phase 2 – sample C.

RESULTS

EEG

We first identified the regions with increased neural activity in phases 1 and 2 (Figure 2). For all three samples, neural activity was higher in the OFC (Brodmann area 11 [BA11]; Montreal Neurological Institute [MNI] coordinates: $X = -5$, $Y = 60$, $Z = -10$), which responds to rewarding behaviors, and in the anterior cingulate cortex (ACC) (BA32; MNI coordinates: $X = -8$, $Y = 40$, $Z = 15$), which is responsible for cognitive judgment and decision-making based on motivation and rewarding emotions. Neural activity in the left frontal gyrus was higher for samples A and B than for sample C (Figure 3).

Next, we compared neural activity in BA11 and BA32 across the three samples for each phase (Table II). In both phases and areas, samples A and B elicited significantly more neural activity than sample C ($p < 0.05$). Sample A also evoked a significantly higher neural activity in phase 2 than in phase 1 in both BA11 and BA32 ($p < 0.05$).

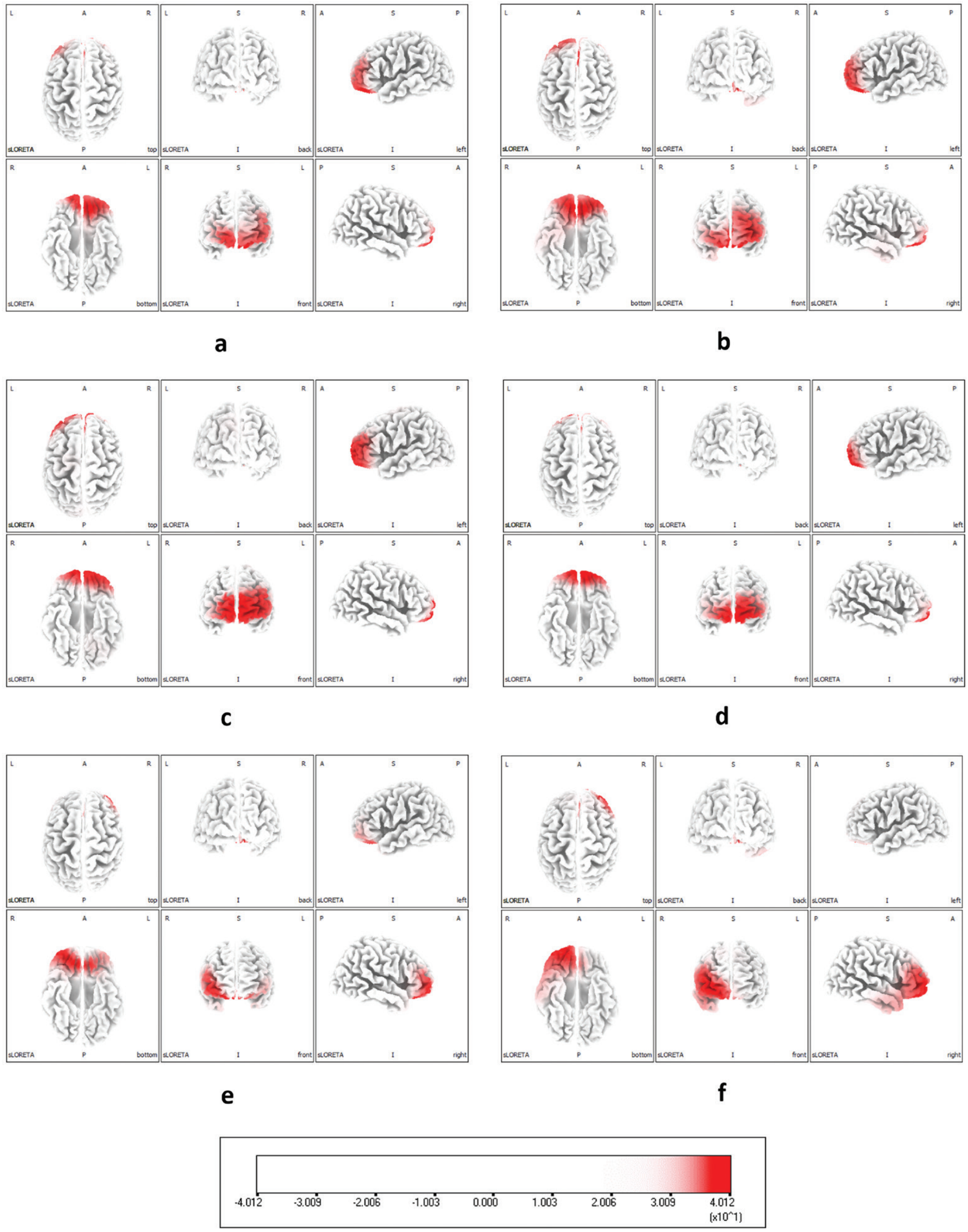

Figure 3. Regions with increased neural activity representing the different emotional responses triggered by reward differences in the foam samples: (**a**) phase 1 – sample A; (**b**) phase 2 – sample A; (**c**) phase 1 – sample B; (**d**) phase 2 – sample B; (**e**) phase 1 – sample C; and (**f**) phase 2 – sample C.

Table II
Comparison of Neural Activity in the Areas BA11 and BA32

	Phase 1			Phase 2			*p*-value		
	Sample A	Sample B	Sample C	Sample A	Sample B	Sample C	Phase	Foam	Interaction
BA11 (μA/mm²)	46.1 ± 7.2†▲	53.4 ± 8.2‡	37.2 ± 8.1†‡	54.5 ± 10.6•▲	52.1 ± 6.0■	32.6 ± 7.9•■	0.65	<0.01	0.02
BA32 (μA/mm²)	38.5 ± 8.7†▲	42.8 ± 8.5‡	28.5 ± 6.1†‡	50.4 ± 6.6•▲	44.2 ± 6.3■	29.0 ± 5.4•■	0.01	<0.01	0.01

Notes: BA = Brodmann area.a
Values are presented as means ± standard deviations.
Phase 1: effect of foam placed on hands; phase 2: effect of foam placed on cheeks.
Sample A: foam with low viscosity; sample B: foam with medium viscosity; sample C: foam with high viscosity.
A two-way ANOVA with a Bonferroni post hoc analysis was performed for statistical evaluation.
† Phase 1 – sample A versus phase 1 – sample C; $p < 0.05$.
‡ Phase 1 – sample B versus phase 1 – sample C; $p < 0.05$.
• Phase 2 – sample A versus phase 2 – sample C; $p < 0.05$.
■ Phase 2 – sample B versus phase 2 – sample C; $p < 0.05$.
▲ Phase 1 – sample A versus phase 2 – sample A; $p < 0.05$.

SALIVARY CORTISOL

The salivary cortisol levels before and after the face-washing procedure using each of the three samples are shown in Table III. There were no significant differences in cortisol levels between the three samples in either the pre- or post-procedure measurements. The magnitudes of the cortisol changes for all samples are shown in Table IV. Cortisol levels changed significantly more in response to sample C than sample A ($p < 0.05$), while the response to sample B was not significantly different from the other two ($p > 0.05$).

DISCUSSION

In this study, we assessed the effect of face-washing on the emotional response of participants using three types of foam with different viscosity levels. For all foam samples, the OFC (BA11), which plays a role in rewarding behaviors, was stimulated in response to experiencing the samples on both the hands (phase 1) and face (phase 2). The neural activities of the OFC (BA11)[16,17] and ACC (BA32),[18,19] which are involved in motivation and cognitive judgment/decision-making based on rewarding emotions, respectively, were significantly higher than those elsewhere in the brain. Given that tactile stimuli can cause changes in cognitive processes and emotions,[8] our results suggest that foam-mediated tactile stimulation may cause an emotional response.

We found that in response to samples A and B, the participants' neural activity was relatively higher in the left cerebral hemisphere than in the right one. In contrast, the signal was higher for the right frontal lobe than for the left frontal lobe in response to sample C in both phases. In a previous study, EEG responses observed during pleasant emotions

Table III
Comparison of Salivary Cortisol

	Pre-test			Post-test			*p*-value		
	Sample A	Sample B	Sample C	Sample A	Sample B	Sample C	Phase	Foam	Interaction
Salivary cortisol (nM)	6.7 ± 4.5	7.1 ± 3.9	5.0 ± 2.3	5.4 ± 2.5	6.2 ± 3.5	7.8 ± 3.9	0.88	0.89	0.21

Notes: Values are presented as means ± standard deviations.
Pre-test: before a series of facial cleansing procedures; post-test: after a series of facial cleansing procedures.
Sample A: foam with low viscosity; sample B: foam with medium viscosity; sample C: foam with high viscosity.
A two-way ANOVA with a Bonferroni post hoc analysis was performed for statistical evaluation.

Table IV
Comparison of Changes in Salivary Cortisol

	Sample A	Sample B	Sample C	*p*-value
Magnitude of salivary cortisol change (nM)	−1.35 ± 3.3 (−6.7 to 2.3)	−0.9 ± 3.6 (−4.8 to 5.7)	2.7 ± 2.4 (−0.5 to 6.5)†	0.03

Notes: Values are presented as means ± standard deviations (minimum value−maximum value).
Sample A: foam with low viscosity; sample B: foam with medium viscosity; sample C: foam with high viscosity.
Magnitude of change = post-test value minus pre-test value.
†Sample A versus sample C; $p < 0.05$.

were higher in the left hemisphere, whereas during unpleasant emotions, they were higher in the right hemisphere.[20] Therefore, we inferred that the tactile stimulation elicited by samples A and B induced more pleasant feelings in the participants, while sample C evoked more unpleasant feelings. Similarly, the salivary cortisol tended to increase from the baseline in response to sample C, while it slightly decreased after using samples A and B, although the changes with each sample before and after treatment were not significant. It has been reported that salivary cortisol levels decrease during relaxation[21,22] and increase under stressful conditions[23,24]; therefore, we inferred that the tactile stimulation and facial cleansing experience with sample C (with high viscosity) were more stressful than those with samples A and B. Conversely, samples A and B (with low and moderate viscosity, respectively) seemed to evoke more pleasant feelings.

Previous studies reported that pleasant tactile stimuli cause a significant increase in neural activity in the OFC (9) and ACC.[25] The EEG measurements in the current study demonstrated that the neural activity in BA11 and BA32 was significantly higher in both phases using samples A and B than with sample C. Therefore, we conclude that the tactile stimuli of samples A and B evoked more pleasant emotions than those of sample C.

We further found that upon stimulation with sample A, the recorded neural activity in both BA11 and BA32 was significantly higher in phase 2 than in phase 1. This suggests that participants' emotions changed between perceiving the foam on their hands and perceiving the foam on faces. BA11 responds to sensory input and generates value representations by encoding combinations of stimuli, leading to motivated behavior.[16] In addition, BA32 (the ACC region) is also involved in generating value representations, and its emotional processing function is generally considered to induce motivation. The ACC plays an important role in inferring and judging current and future situations based on extrinsic experiences from the external environment, leading to appropriate behavior.[26] This information may help us understand the effects observed upon foam application to the face. During the foam application to the cheeks in phase 2, before spreading it upon the whole face, neural activity in these brain regions may have been stimulated by enhanced motivation toward the act of washing the face, based on the positive experience of tactile stimulation in phase 1. However, the reason this tendency was observed only with sample A remains unclear.

This study has several limitations: first, the number of participants was small ($n = 12$), and only females were included. Future studies should enroll a greater number of participants, including males. Second, in addition to its viscosity, other properties of the foam were not considered. Thus, subsequent studies should investigate the effects of other relevant characteristics on participants' emotions, such as foam density and shape retention. Third, we only examined some aspects of face-washing. In the future, it will be necessary to examine changes in neurophysiological indices throughout the whole face-washing procedure.

Despite these limitations, our results indicate that the potential emotional changes evoked by different tactile stimulation according to foam viscosity can be captured via neurophysiological indices, and that these emotions can change during specific segments of the face-washing procedure. We believe that our findings will provide valuable information for developers of facial cleansers and hand soaps. They will also be useful for investigating other foam characteristics and in designing research to develop products that improve the users' physical and emotional experience.

CONCLUSION

This study investigated the effects of foam with different viscosities used as tactile stimuli, on the emotions of healthy female adults using neurophysiological indices. The tactile stimulation-induced changes in these indices in relation to the foam viscosity indicate that pleasant feelings were evoked by low and medium viscosity foams and more stressful emotions were associated with the high viscosity foam. These results also suggest that neurophysiological indices, such as EEG and salivary cortisol, can be useful for comparing user experiences across different products.

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DATA AVAILABILITY

The data generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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