

# Cortical Activation Patterns During Visual and Vibrotactile Emotion Stimulation: A Comparative fNIRS Study

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**Abstract**—This study provides the comparison of prefrontal cortical activation during visual versus conditioned haptic emotion stimulation using functional Near-InfraRed Spectroscopy. Using a within-subject design with classical conditioning, 32 participants learned associations between facial expressions and vibrotactile patterns. Results showed no significant difference in prefrontal oxygenated hemoglobin concentration between modalities ( $p = .640$ ), supporting modality-independent emotion processing. However, haptic processing required significantly higher cognitive effort as measured by the NASA Task Load Index (NASA-TLX) Mental Demand subscale ( $p = .001$ ,  $r = .57$ ). Recognition rates were comparable (94.8% visual, 93.8% haptic). These findings suggest that haptic emotion communication systems are neurally viable but may require extended training to reduce cognitive demands. The results have implications for the development of assistive technologies that could enable blind and visually impaired individuals to access non-verbal emotional information through the tactile channel.

**Index Terms**—haptic emotion communication; cross-modal processing; prefrontal cortex; cognitive load; assistive system.

## I. INTRODUCTION

When people talk to each other, the spoken word is only a fraction of what is actually communicated. A raised eyebrow can signal skepticism, a fleeting smile can suggest agreement, an averted gaze can reveal disinterest [1]. This non-verbal communication, such as facial expressions, gestures, or eye contact, accounts for over 50% of emotional information exchange in conversations [1].

For the 2.2 billion people worldwide with visual impairments, including 36 million who are completely blind [2] [3], this visual dimension of human interaction remains systematically inaccessible. Without visual cues, affected individuals cannot recognize whether a statement is meant ironically, approvingly, or disapprovingly. Such information is typically derived from facial expressions and gestures [4], leaving them without a central source of information for understanding social situations. This situation is referred to as “conversational asymmetry,” an imbalance in which sighted conversation partners have access to all communication channels, while visually impaired individuals can only receive verbal and auditory information [5]. This asymmetry affects not only individual

conversations but the fundamental ability to build trust and maintain social relationships [5].

Existing assistive technologies for visually impaired people, such as screen readers, speech synthesis, or acoustic signals, primarily rely on auditory output [6]. In social interactions, these solutions reach their limits: Auditory cues interrupt conversations, occupy the already heavily used auditory channel, and are perceptible to outsiders, preventing discretion [6]. The tactile channel offers a promising alternative: It can be used in parallel with auditory communication and enables discrete information transmission during ongoing conversations [7].

Research has demonstrated that emotions can be communicated through touch [4]. Liu et al. [7] transferred this principle to technical systems. Their programmable vibrotactile interface is based on elastomer actuators that generate vibrations in the frequency range of 50–450 Hz and enable four-dimensional haptic stimulation (time, position, amplitude, frequency) [7]. Users achieved emotion recognition rates of 64.6% without prior training; after systematic learning training, this increased to 95.8% [7]. Although these results demonstrate the behavioral effectiveness of haptic emotion transmission, there has been no neurophysiological study to date that clarifies whether haptic stimuli evoke the same cortical activation patterns as visual emotional stimuli [8].

The behavioral successes of Hertenstein et al. [4] and Liu et al. [7] demonstrate that humans can recognize emotions through haptic stimuli. However, high recognition rates only show that emotional information arrives, not whether the brain processes this information in the same way as visual stimuli [7]. It remains unclear whether haptically transmitted emotions activate the same neural networks as visual stimuli. Research on cross-modal emotion processing suggests that the brain may process emotional information independently of the sensory input modality [9]. Klinge et al. [10] also showed increased amygdala activation in blind participants during emotional auditory stimuli.

Even with comparable activation patterns, the question of cognitive costs arises. Cognitive Load Theory [11] postulates capacity-limited working memory resources; decoding unfamiliar stimulation modalities could require additional processing resources [12].

Despite established evidence for behavioral effectiveness of haptic emotion transmission and cross-modal emotion processing, a direct neurophysiological comparison of visual and haptic emotion stimulation is lacking [8].

Based on the identified research gap, this study addresses the following research question: Does emotional processing differ between haptic and visual modalities?

This study has several limitations, including the restriction of fNIRS to cortical surface activity, the relatively small sample size, and potential additional cognitive demands introduced by the conditioning paradigm.

The remainder of this paper is organized as follows. Section II reviews related work on haptic emotion communication, neural foundations of cross-modal processing, and functional Near-Infrared Spectroscopy (fNIRS) in emotion research. Section III describes the methodology, including study design, stimuli, and measurement procedures. Section IV presents the results. Section V discusses the findings and their implications. Section VI concludes the paper and outlines future work.

## II. RELATED WORK

This section reviews the theoretical and empirical foundations relevant to the present study.

### A. Haptic Emotion Communication

Can humans understand emotions through touch alone? Hertenstein et al. [4] investigated this question in an experiment in which participants communicated eight different emotions exclusively through touching another person's arm, without words, facial expressions, or eye contact. Recipients recognized emotions with remarkable accuracy: Anger was correctly identified in 78% of cases, fear in 75%, disgust in 68%, and happiness in 83% (chance level: 12.5%). The researchers identified characteristic touch patterns: Anger was conveyed through short, intense touches; sadness through slow, gentle contact; joy through rhythmic, dynamic movements [4].

Liu et al. [7] transferred these findings to technical systems. Their flexible haptic interface uses elastomer actuators generating vibrations in the range of 50-450 Hz. In their study, users achieved emotion recognition rates of 64.6% for six basic emotions without prior training. After a systematic learning program, this increased to 95.8%, evidence that the brain can learn to associate vibration patterns with emotional meanings [7].

### B. Neural Foundations of Cross-Modal Emotion Processing

For developing haptic emotion systems, it is crucial whether the brain can process emotions independently of the sensory channel. The meta-analysis by Lindquist et al. [9] provides important theoretical foundations: The absence of modality-specific emotion centers suggests that emotional information from different sensory channels could be processed in the same neural networks.

Klinge et al. [10] provided direct experimental evidence for this adaptability in a functional magnetic resonance

imaging (fMRI) study. fMRI is an imaging technique that visualizes brain activity through changes in blood oxygenation and offers high spatial resolution [13]. The researchers compared brain activity of 12 congenitally blind and 12 sighted participants while both groups listened to emotional voices (fearful, angry, neutral). The central finding: Blind participants showed significantly stronger amygdala activation for emotional compared to neutral voices. The amygdala is an almond-shaped structure in the temporal lobe that plays a key role in evaluating the emotional relevance of stimuli [14]. Particularly revealing was the finding that the strength of amygdala activation correlated with individual recognition performance ( $r = .54$ ). These results demonstrate that the emotional brain, when lacking a sensory channel, increasingly uses the remaining channels for emotional processing [10].

Theoretically, cross-modal emotion processing can be explained by Embodied Cognition, according to which bodily experiences, including haptic perception, are closely linked to cognitive and emotional processes [15]. Multiple Resource Theory [12] also postulates that processing new or unfamiliar stimuli requires more cognitive resources than automated processes.

### C. fNIRS in Emotion Research

Compared to fMRI, fNIRS offers crucial advantages for studies with haptic stimulation. Participants can move, the device is portable, and measurement occurs under naturalistic conditions without the constraints of an MRI scanner [16]. The prefrontal cortex is particularly accessible for fNIRS and shows reliable emotion-related activation patterns [17].

Sánchez-Reolid et al. [8] demonstrated the validity of fNIRS for emotion recognition in a recent study. The researchers presented participants with emotion-inducing images from the IAPS database and classified the evoked emotions (happiness, sadness, fear, anger) based on valence and arousal according to Russell's Circumplex Model. With a 22-channel fNIRS setup over the prefrontal cortex and a Bagging-Trees algorithm, they achieved 64% classification accuracy. A value well above chance level that confirms the suitability of fNIRS for emotion research. While fNIRS has been successfully used to measure emotional responses to visual stimuli, a direct comparison with haptic emotion stimulation is lacking [8] [7].

Based on these findings, two hypotheses were formulated:

**H1:** When haptic emotion stimuli are tested, the prefrontal cortex is activated equally as with visual emotion stimuli.

**H2:** When haptic emotion stimuli are tested, the subjectively perceived cognitive load is higher than with visual emotion stimuli.

## III. METHODOLOGY

This section describes the study design, stimuli used, measurement procedures, and experimental protocol.

### A. Study Design and Sample

The study uses a within-subject design with classical conditioning paradigm. In a learning phase, associations between visual emotion stimuli and emotion-specific vibration patterns were established. Subsequently, it was tested whether haptic stimuli without visual information evoke comparable cortical activation. N = 32 participants were recruited following standard inclusion criteria (age > 18, normal or corrected-to-normal vision, no known neurological disorders). Participation was voluntary and conducted in accordance with institutional ethical guidelines, with informed consent obtained from all participants.

### B. Visual Stimuli

Six emotion categories (happiness, sadness, fear, anger, disgust, neutral) from the FACES database were used [18]. The FACES database was chosen because it offers standardized, validated facial expressions with high recognition rates and is established in emotion research [18]. For each emotion, two images (one female, one male model) were presented alternately (Image1 → Image2 → Image1 → Image2), so that each emotion was shown four times. Using both genders increases the generalizability of results and controls for possible gender-specific differences in emotion perception.

### C. Haptic Stimulation System

For haptic stimulation, a vibrotactile stimulation system was employed. The system consists of vibration motors attached to the fingers and wrist of the non-dominant hand. The non-dominant hand was chosen because it is less accustomed to fine motor tasks in everyday life, requiring increased conscious attention to tactile stimuli [19]. Each emotion was assigned to a specific finger, with assignment randomized, as emotional meaning is established through associative learning during the conditioning phase [14]. The haptic system was chosen because it enables discrete, non-intrusive information trans-mission and does not occupy the auditory channel, which are essential requirements for assistive technologies for visually impaired people [6].

### D. fNIRS Measurement

Brain activity was measured using fNIRS. fNIRS is based on the principle that near-infrared light (760-850 nm wave-length) penetrates skull bone and brain tissue but is absorbed by hemoglobin. Active brain regions require more oxygen, causing blood to flow more strongly to these areas, changing the ratio of oxygenated (HbO) to deoxygenated hemoglobin (HbR). This change is measurable through light absorption [13].

For measurement, the Artinis Brite24 system with 27 channels was used with a frontal headband over the prefrontal cortex. The optodes covered Fp1, Fp2, F3, F4, F7, F8 (10-20 system). The mean HbO concentration across all channels served as an indicator of prefrontal activity. fNIRS was preferred over fMRI because, as already mentioned, participants can move around, the device is portable, and measurements are taken under natural conditions without the restrictions of an MRI scanner, which is an essential

prerequisite for studies involving haptic stimulation [16]. The sampling rate was 25 Hz.

### E. Assessment of Cognitive Load

The NASA Task Load Index was used to assess cognitive load [20], capturing subjectively perceived workload across six dimensions, including mental demand and frustration. The NASA-TLX was chosen because haptic emotion recognition may require more cognitive resources than familiar visual processing [11]. Assessing cognitive load is crucial for evaluating the everyday practicality of assistive systems, as excessive demands would limit practical usability in daily life [6] [11].

### F. Experimental Procedure

Study duration was planned at 35 minutes per participant. The experimental protocol consisted of three consecutive phases.

In the conditioning phase, participants learned the assignment between FACES images and vibration patterns. The experimenter explicitly named each emotion (e.g., “Now follows happiness”) to support conscious linking between visual and haptic stimulus. A memory check at the end of the phase ensured that all assignments were correctly learned, with error free reproduction of all six assignments as the criterion [21]. Stimuli followed standardized timing. In the visual phase, after a 10s baseline, each emotion was shown four times for 4s, separated by 5s pauses. In the haptic phase, a 10s baseline preceded vibrations of approximately 200 ms, also separated by 5s pauses. The baseline served as a resting-state reference for all activations.

After successful conditioning, the visual test phase followed. Participants viewed FACES images without accompanying vibration and verbally reported the perceived emotion after each block. Responses were not corrected to avoid influencing the data. Brain activity was continuously recorded via fNIRS, followed by completion of the NASA-TLX to assess subjective cognitive load.

The haptic test phase concluded the experiment. With eyes closed, participants received vibration stimuli only to assess whether conditioned associations allowed correct emotion identification via haptic stimulation alone. Verbal emotion reports followed each block during continuous fNIRS recording, and the NASA-TLX was administered again to compare cognitive load between conditions.

## IV. RESULTS

This section presents the results in four subsections: sample description, fNIRS findings, emotion recognition rates, and subjective cognitive load.

### A. Sample

Thirty-two participants took part in the study (16 female, 16 male). Age ranged from 20 to 50 years (M = 26.38, SD = 5.70). Thirty-one participants were right-handed, one person was left-handed. All participants had normal or corrected vision. Participation was voluntary and required written consent.

B. fNIRS Results

fNIRS measures changes in the concentration of oxygenated hemoglobin in cortical blood vessels of superficial brain regions. An increase in HbO value indicates increased neural activity, as active brain areas are supplied with more oxygen-rich blood [16]. Values are given in micromoles per liter ( $\mu\text{mol/L}$ ) and calculated relative to baseline (resting state).

The fNIRS data were processed using a Python script (version 3.9) with pandas, numpy, and scipy. Processing included artifact removal, event marker identification (S1 for visual, S2 for haptic phase), emotion block segmentation, and baseline correction using a 10-second rest period (250 data points at 25 Hz). As a block design with multiple stimuli per emotion block was employed, the mean HbO across each block served as the dependent measure, capturing the cumulative hemodynamic response rather than individual stimulus-evoked responses. Statistical analysis focused on the prefrontal cortex (PFC), as fNIRS primarily captures cortical surface activity and the PFC plays a central role in cognitive-emotional processing [22]. To avoid pseudo-replication, HbO values were first averaged across all prefrontal channels per emotion and condition then across the six emotions per participant, yielding one mean HbO value per condition and participant ( $N = 32$  paired observations). The Shapiro-Wilk test revealed significant deviations from normal distribution for both conditions (visual:  $W = .722, p < .001$ ; haptic:  $W = .463, p < .001$ ); therefore, the nonparametric Wilcoxon signed-rank test was applied. Descriptive statistics are summarized in Table I.

TABLE I. DESCRIPTIVE STATISTICS AND WILCOXON TEST FOR PREFRONTAL HBO CHANGES

Stimulation	N	M ( $\mu\text{mol/L}$ )	SD	Z	p
Visual	32	-0.85	10.41	-0.47	.640
Haptic	32	5.93	15.74		

Note. N = number of participants (paired observations); M = mean; SD = standard deviation; Z = Wilcoxon signed-rank test statistic; p = significance value. Positive HbO values indicate an increase relative to baseline.

The Wilcoxon signed-rank test revealed no statistically significant difference between visual and haptic stimulation in the prefrontal region ( $Z = -0.47, p = .640$ ). Descriptively, haptic stimulation was associated with a mean increase in HbO of  $5.93 \mu\text{mol/L}$ , whereas visual stimulation showed a slight decrease of  $-0.85 \mu\text{mol/L}$ . Emotion-specific results are presented in Table II.

TABLE II. WILCOXON TESTS FOR VISUAL VS. HAPTIC PER EMOTION (PREFRONTAL REGION)

Emotion	Z	p	r
Sadness	-0.49	.627	.035
Anger	-0.08	.940	.006
Neutral	-0.66	.513	.048
Fear	-0.90	.369	.065
Happiness	-1.48	.140	.107
Disgust	-1.38	.166	.100

Note. All tests two-tailed. Z = Wilcoxon signed-rank test statistic; p = significance value; r = effect size ( $r = Z / \sqrt{N}$ )

Emotion-specific analyses revealed no significant differences between modalities (all  $p > .05$ ). Small effect sizes were consistent with the absence of significant differences between modalities. In summary, the fNIRS results show that haptic emotional stimulation activates the prefrontal cortex at a level comparable to visual stimulation. The activation patterns do not differ significantly between the two modalities.

C. Emotion Recognition

Emotion recognition accuracy was captured through verbal responses after each emotion block. In the visual condition, 182 of 192 assignments were correct (94.8%). In the haptic condition, 180 of 192 were correct (93.8%), representing a difference of only 1.0 percentage points. Recognition rates are shown in Table III.

TABLE III. EMOTION RECOGNITION RATES BY PHASE AND EMOTION

Emotion	Visual		Haptic	
	correct/total	%	correct/total	%
Sadness	28/32	87.5	27/32	84.4
Anger	31/32	96.9	31/32	96.9
Neutral	32/32	100.0	32/32	100.0
Fear	28/32	87.5	28/32	87.5
Happiness	32/32	100.0	31/32	96.9
Disgust	31/32	96.9	31/32	96.9
Total	182/192	94.8	180/192	93.8

The highest recognition rates were observed for Neutral (100% in both phases) and Happiness (100% visual, 96.9% haptic). These results confirm successful conditioning and reliable stimulus identification in both modalities.

D. Subjective Cognitive Load (NASA-TLX)

Subjective cognitive load was captured using the NASA-TLX [20]. The NASA-TLX is a multidimensional instrument for assessing subjective workload and comprises six subscales: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration. Subjective workload results are summarized in Table IV.

TABLE IV. NASA-TLX RESULTS: COMPARISON OF VISUAL AND HAPTIC STIMULATION

Scale	M vis	SD vis	M hap	SD hap	Z	p
Total	173.81	56.36	187.28	71.16	1.81	.070
Mental Demand	23.44	15.83	38.13	19.19	3.21	.001

Note. Wilcoxon signed-rank test for paired samples. M = mean; SD = standard deviation; Z = Wilcoxon signed-rank test statistic; p = significance value.

The NASA-TLX total score showed no significant difference between conditions ( $Z = 1.81$ ,  $p = .070$ ). However, the Mental Demand subscale showed a highly significant difference ( $Z = 3.21$ ,  $p = .001$ ) with large effect size ( $r = .57$ ) [23]. At the individual level, 24 of 32 participants (75%) reported higher mental demand during haptic stimulation.

These results show that processing haptic emotional stimuli is associated with significantly higher cognitive demand than processing visual stimuli.

## V. DISCUSSION

Results support H1: No significant difference was found between conditions ( $p = .640$ ), indicating comparable prefrontal activation. Descriptively, haptic stimulation showed higher activation ( $M = 5.93 \mu\text{mol/L}$ ) compared to visual stimulation ( $M = -0.85 \mu\text{mol/L}$ ), though this did not reach significance due to high interindividual variability. H2 was confirmed: The Mental Demand subscale showed a highly significant difference ( $p = .001$ ,  $r = .57$ ). The high recognition rates (94.8% visual, 93.8% haptic) confirm successful conditioning and demonstrate that haptic emotion communication can achieve nearly equivalent accuracy to visual recognition.

The finding that prefrontal activation did not differ significantly has important theoretical implications. According to cognitive emotion regulation models [24], the prefrontal cortex evaluates emotional stimuli independently of sensory input modality. This aligns with cross-modal plasticity research [25]. The successful conditioning phase appears to have led to haptic stimuli activating similar prefrontal networks as visual stimuli, supporting modality-independent emotional representations at higher cortical levels. The emotion-specific analysis reinforces this: no significant differences for any emotion category, suggesting a general pattern consistent with Embodied Cognition theories [15].

The significant difference in Mental Demand reveals an important distinction: While neural activation is comparable, cognitive effort differs considerably. Processing haptic stimuli requires identifying vibration patterns and retrieving learned associations, while visual emotion recognition occurs automatically [26]. Visual recognition is automated through lifelong experience. Humans recognize

emotional expressions from early childhood [27], whereas haptic coding is learned only during a brief conditioning phase. This aligns with Multiple Resource Theory [12]. The specificity of the effect is noteworthy: While the NASA-TLX total score did not differ significantly, the Mental Demand subscale showed a highly significant difference. This suggests that haptic processing selectively increases cognitive demand without affecting other aspects of workload, such as physical effort or frustration. One plausible explanation is that the haptic condition requires an additional layer of meaning-construction: participants must sustain a technically mediated representation and continuously map it onto socially learned emotional categories. Related work on technically mediated self-representation indicates that changes in representational format can affect subjective presence and increase interpretive processing demands, even when task accuracy remains high [35].

These findings are directly relevant for haptic assistive systems for blind and visually impaired people. Neural equivalence suggests haptic systems could provide functionally similar emotional information access at the level of prefrontal cognitive-emotional evaluation. However, increased cognitive load could be problematic in real-world applications where resources may be limited [28]. The high recognition rates (93.8% haptic) and potential reducibility of cognitive load through extended training support practical viability. Our haptic recognition rates (93.8%) exceed previous studies (50-78%) [4] [29], likely due to the explicit conditioning paradigm enabling more reliable retrieval. The comparable prefrontal activation extends previous fNIRS emotion research [16] to cross-modal communication.

Several limitations should be considered. fNIRS cannot capture deeper structures (amygdala, ACC, insula) central to emotion processing [30]; complementary fMRI studies would be necessary. Optode placement followed standardized landmarks, but anatomical correspondence may vary [31]. Findings from sighted participants may not generalize to blind individuals, who show different cortical organization [32] [33]; future studies should investigate whether they show increased efficiency in haptic processing. The FACES database excludes Surprise [34], and haptic patterns lacked empirical pre-validation [4] [29]. Manual stimulus triggering and fixed phase order prevent precise timing verification and counterbalancing. The increased prefrontal activation during haptic stimulation could reflect cognitive translation processes (retrieving learned associations) rather than emotion processing per se. A clear separation between emotional activation and cognitive demand is not possible with the present design.

## VI. CONCLUSION AND FUTURE WORK

This study provides fNIRS-based evidence for the assumption that conditioned haptic emotion stimulation activates the prefrontal cortex to the same extent as visual emotion stimulation. The absence of significant differences in prefrontal HbO concentration ( $p = .640$ ) supports the hypothesis that emotion processing operates at a modality-independent level after successful conditioning.

However, haptic emotion processing requires significantly more cognitive effort, as demonstrated by the highly significant difference in NASA-TLX Mental Demand scores ( $p = .001$ ,  $r = .57$ ). This dissociation, characterized by comparable neural activation but increased cognitive load, has important implications for the design of assistive technologies. Haptic emotion communication systems appear to be neurally viable but may require structured training programs to achieve the level of automation typically associated with visual emotion recognition.

Recognition rates were comparable between modalities (94.8% visual, 93.8% haptic), demonstrating that haptic emotion communication can achieve nearly equivalent accuracy to visual recognition after appropriate conditioning.

Future research should extend this paradigm to blind and visually impaired populations to determine whether cross-modal plasticity enhances haptic emotion processing efficiency in this target group. Additional research directions include longitudinal studies on training effects on cognitive load, automated stimulus presentation for better temporal precision, and integration with fMRI to capture subcortical activation patterns.

Future work should also explore real-world applications and social use cases, such as supporting social interaction and everyday communication for visually impaired individuals.

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