Modelling the early affect response to vibrotactile stimulation in the cortex: A source-based spatiotemporal analysis

Suranjita Ganguly, Aditya Koppula, and Kousik Sarathy Sridharan

Abstract—**Touch-mediated affect has largely been studied using natural textures and brushing techniques, which present challenges in control and deployment across haptic applications. A common alternative is vibrotactile stimulation (VBT) since it is easily deployable and accessible across devices. However, sparse literature exists on the VBT-induced affect modulation and its cortical correlates. Addressing this gap, we developed a novel paradigm that examined the behavioral and electrophysiological correlates of affect induced by VBT. We used electroencephalography (EEG) to record the cortical responses to VBT across six different locations and measured the concurrent affect ratings. Mixed effects modelling, an unsupervised modelling technique, was used to decipher the relationships between stimulation conditions, affect ratings and cortical modulations. Our study revealed that altering the duration of the vibrotactile stimuli can elicit distinct affect. The location of the VBT stimuli did not play a part in the perceptual aspects of affect but was involved in the cortical encoding of affect. Furthermore, early cortical processing in the somatosensory cortex (SCx) primarily encoded Arousal and not Valence. Our study lays out phenomenological aspects of cortical VBT processing and lays the groundwork for future research.**

Index Terms— **affect, electroencephalography, somatosensory cortex, source localization, vibrotactile stimulation**

I. INTRODUCTION

T OUCH is a complex perception induced by the stimulation of receptors in the skin or their afferents and is most commonly evoked by the physical contact of the skin with an object. The nature of tactile experience is determined in part by the "*atomistic* attributes" of the touch stimulus viz., spatial extent of the stimulus (area of stimulation), site of stimulation, duration, amplitude (depth of skin indentation), frequency, temperature, consistency, texture etc. Tactile stimulation can have multi-fold effects on human physiology. Besides tactile discrimination (of object properties), touch can strongly influence affect. Affect refers to the emotional state of mind, and it has two salient aspects in the context of touch perception viz., 'Valence' and 'Arousal'. Valence is the term applied to the quality of stimulus and is often described in terms of its pleasantness/unpleasantness. Arousal denotes the state/level of wakefulness and is strongly modulated by the intensity of stimulus. The modulation of tactile affect has been extensively studied using natural tactile stimuli like fabrics of distinct hedonic values [1]–[5] and brush strokes on the skin at different forces and velocities [6]–[10]. While the affect sensations elicited by fabric/brush strokes closely simulate natural touch, they do not allow us to dissect the relative contributions of the different atomistic touch attributes on the Valence/Arousal response to touch. Such information can be crucial to optimize the design of devices that are based on touch, like haptic technology. In addition, fabric-based studies have already shown differential modulation of affect to the stimulation of various body sites [1], [2], [11] due to the differences in distributions of sensory receptors [12], a critical aspect that remains unexplored.

An alternative mode of exploration of touch perception is vibrotactile stimulation (VBT). In contrast to fabric/brush stimulus, VBT allows finer evaluation of the effects of different touch attributes in a controlled manner. However, the relationship between VBT and tactile affect is uncertain for the following reasons. Natural touch is mediated by large diameter fibers (innervating the four cutaneous mechanoreceptors viz., Meissner's corpuscles, Pacinian corpuscles, Merkel's discs & Ruffini's end organs) and small diameter unmyelinated C-tactile fibers that transmit information through the corresponding central afferent pathways consisting of the dorsal column-medial lemniscal and spinothalamic pathways respectively. The large diameter fibers carry information required for discriminative aspects of the touch, while the C-tactile fibers are responsible for affective aspects of touch (evoked by stimuli such as fabrics, interpersonal touch, light stroking with a brush etc.). VBT is known to preferentially activate the Meissner's and Pacinian corpuscles, the receptors that contribute to discriminative touch. Therefore, it is uncertain if VBT can elicit tactile affect as it engages only a subset of tactile mechanism corresponding to discriminative touch [13][7], [14][15].

To our knowledge, only two studies [16], [17] have attempted to explore the VBT modulation of affect, by varying the different VBT parameters (such as amplitude,

Suranjita Ganguly is with the Department of Biomedical Engineering, Indian Institute of Technology, Hyderabad, India (email: BM19RESCH11002@iith.ac.in).

Aditya Koppula was with the Indian Institute of Technology, Hyderabad, India. He is now with the Department of Physiology, Apollo Institute of Medical Sciences and Research, Jubilee Hills, Hyderabad, India (e-mail: aditya2171985@gmail.com).

Kousik Sarathy Sridharan is with the Department of Biomedical Engineering, Indian Institute of Technology, Hyderabad, India (email: ks@bme.iith.ac.in).

duration and frequency) and obtaining concurrent behavioral ratings from the subjects. The study [16] recorded the affect elicited in subjects by touching the screen of a smartphone that imparted VBT upon contact. These ratings were mapped into the 2D circumplex model of the affect [18], where affect is quantitatively described in terms of the two independent, linear scales, viz., Valence and Arousal. Another study [17] conducted a similar experiment with 5 different scales, Arousal being one of them. Both studies found that VBT elicited affect as a function of amplitude wherein stimulation amplitude correlated positively with Arousal ratings. The study [16] also found a positive correlation between the stimulation frequency and rating scales. However, [16] showed a positive correlation between stimulation duration and arousal, while [17] could not replicate the same. These results indicate that the already sparse VBT-affect literature is ridden with inconsistencies that await further experimental clarification.

The cortical electrophysiology of VBT-induced tactile affect is another dark alley in the VBT-Affect literature. In the context of developing neurofeedback-based applications, a mapping between VBT-stimulus properties and induced cortical electrophysiology (corresponding to desirable/undesirable affect state) from an individual subject, can potentially enable us to tailor the VBT to achieve the beneficial/desired effects vis-a-vis the cortical electrophysiology (and therefore the affect state). The only available insights on the relevant tactile affect related to cortical signature are from fabric- or brush-stroke-based studies. Functional magnetic resonance imaging (fMRI) and electroencephalography (EEG) studies based on those naturalistic stimulation protocols have demonstrated altered cortical connectivity, and correlation of the elicited affect ratings with the magnitude of activations across several brain structures such as the prefrontal cortex, anterior cingulate cortex (ACC), somatosensory cortex (SCx), insula and amygdala[3], [5], [6], [8], [19]–[21].

Among the various brain structures, SCx is of particular interest in relation to the tactile affect. Although it is the primary cortical structure involved in the tactile processing of discriminative touch [22]–[27], responses from the SCx have been shown to be modulated, when affect was induced by other modalities of stimulation such as visual stimulation [28], [29]. Affective disorders like stress [30], depression [31], [32] and bipolar disorder [33] have also shown abnormal modulations in the SCx indicating that SCx may at least partially encode affect. Therefore, it may prove to be beneficial to investigate the affect-related modulation of the SCx whilst developing haptic-based applications.
The current study deploys VBT across multiple body sites to record the cortical and behavioral changes due to the affect induced by VBT. Three stimuli were chosen such that they were sufficiently separated in the 2D circumplex model [16], [17] by modulating the frequency, duration and interstimulus intervals. The stimuli were deployed across six locations on the body viz. the index finger, arm, abdomen, back, leg and toe. The locations were chosen on account of their extensive use in day-to-day interactions, clinical prognosis, and usage in haptic feedback systems in various environments such as home, work, vehicles etc. The cortical responses were recorded with the help of EEG and the behavioral responses were manually noted. The EEG data was projected back into pseudo-individualized MRIs to obtain the source activations around the two somatosensory areas viz. the SI and the SII (indicated by the anatomical regions of the post-central and supramarginal gyri respectively). We hypothesized the following: (i) The affect induced by VBT is also encoded by the cortical structures that are known to process discriminative aspects of tactile sensibility induced by the VBT, (ii) There is a differential VBT-related affect modulation in cortex and affect ratings in relation to various stimulation locations (iii) The electrocortical activations co-vary to the affect ratings.

II. METHODS

A. Subjects

19 subjects (8 females) with no self-reported history of somatosensory deficits were recruited from the institute for the study. The subjects were all right-handed, as evaluated by the Edinburgh handedness inventory. The descriptive statistic on the subjects is listed in the Supplementary Material. Ethical approval for experimentation was taken from the Institute's ethical committee. All experiments were carried out following the Declaration of Helsinki. The subjects were briefed about the experiment before their participation. Informed consent was taken from them for data storage and analysis. They were free to abort the experiment anytime without any penalty.

B. Experimental Paradigm

The schematic diagram of the experimental paradigm is shown in Fig. 1. Three types of stimuli (henceforth referred to as Stim 1, Stim 2 and Stim 3), varying in frequency, duration and inter-stimulus intervals (See Table I for details) were deployed across six different locations viz. two on the upper limb (index finger and upper arm), two on the trunk (back and abdomen) and two on the lower limb (toe and leg). This resulted in a total of 18 combinations of stimulation conditions (Stimulus* Location), which were pseudorandomized between subjects.
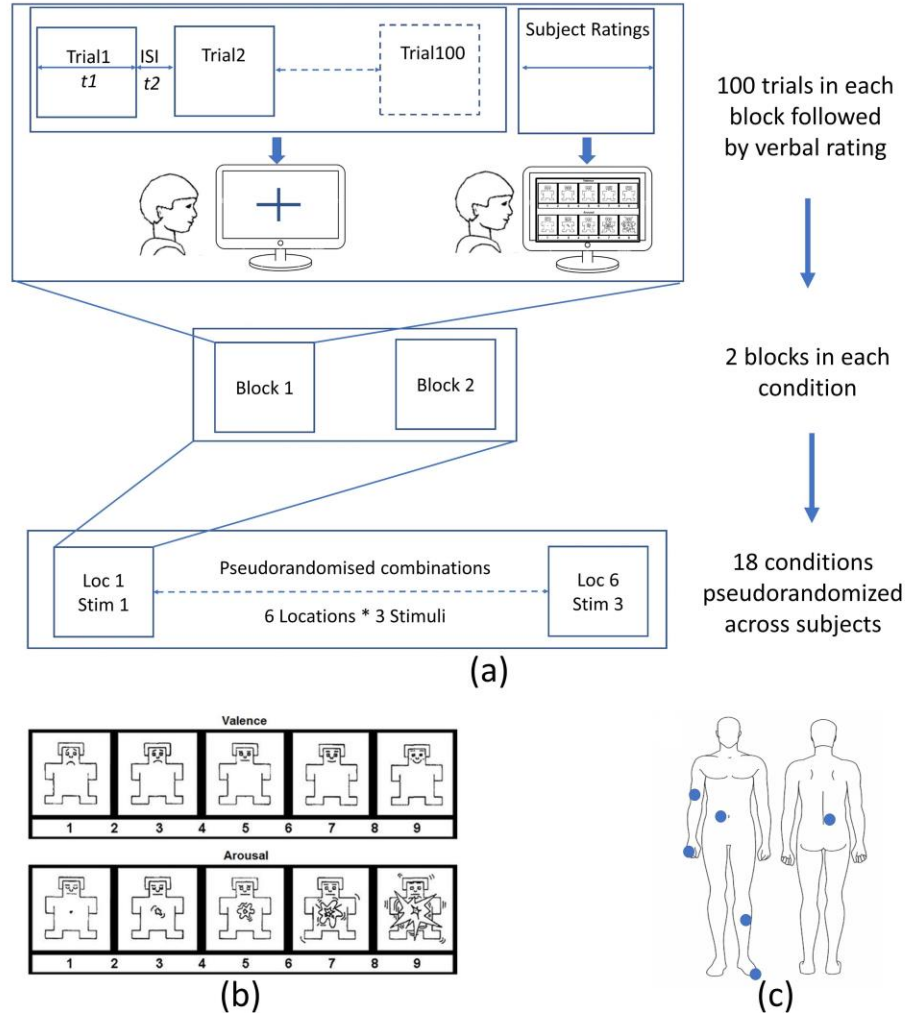
Fig. 1. (a) The schematic diagram of the experimental paradigm is shown. There are a total of 18 conditions (8 locations* 3 stimuli) that are pseudorandomized across subjects. Under each condition, 200 stimuli are deployed in two blocks (100 stimuli each) followed by affect ratings for each block (b) The SAM scale used to obtain Valence and Arousal ratings from the subjects is shown. The scale depicts Valence and Arousal ratings as pictograms, facilitating the visualization of the degree of affect induced (c) A schematic diagram of the six locations of stimulation is shown. All stimuli were deployed in the dominant side of the subject, which in our case is the right side of the body.

TABLE I

STIMULUS SETTINGS USED IN TO EXPERIMENT

Stimulus	Frequency (Hz)	Duration (ms)	ISI (ms)
Stim 1	300	1000	1500
Stim 2	60	1000	1500
Stim 3	60	50	1000

The subjects were asked to sit comfortably on a chair and all stimuli were deployed on the dominant side (in our case, the right side since all subjects were right-handed) of the subjects. For each combination of stimulation conditions, the stimulus was deployed in one of the six locations in two blocks successively, with each block consisting of 100 repetitions (or trials) of the stimulus with the defined durations and ISIs. The screen in front of the subject displayed a crosshair during the trials and the subject was instructed to focus upon it. After each block, an inter-block interval of 15s was given, during which the screen displayed the two rating scales (described in detail in the subsequent section). This served as a cue for the subject to verbally dictate the affect ratings corresponding to the stimuli, which were manually noted down by the investigator. The location and stimulation conditions were pseudorandomized for every subject resulting in 18 combinations for each subject (6 locations*3 stimuli). The total experimental time was around 2 hours 10 minutes, including 30 minutes of subject preparation time.
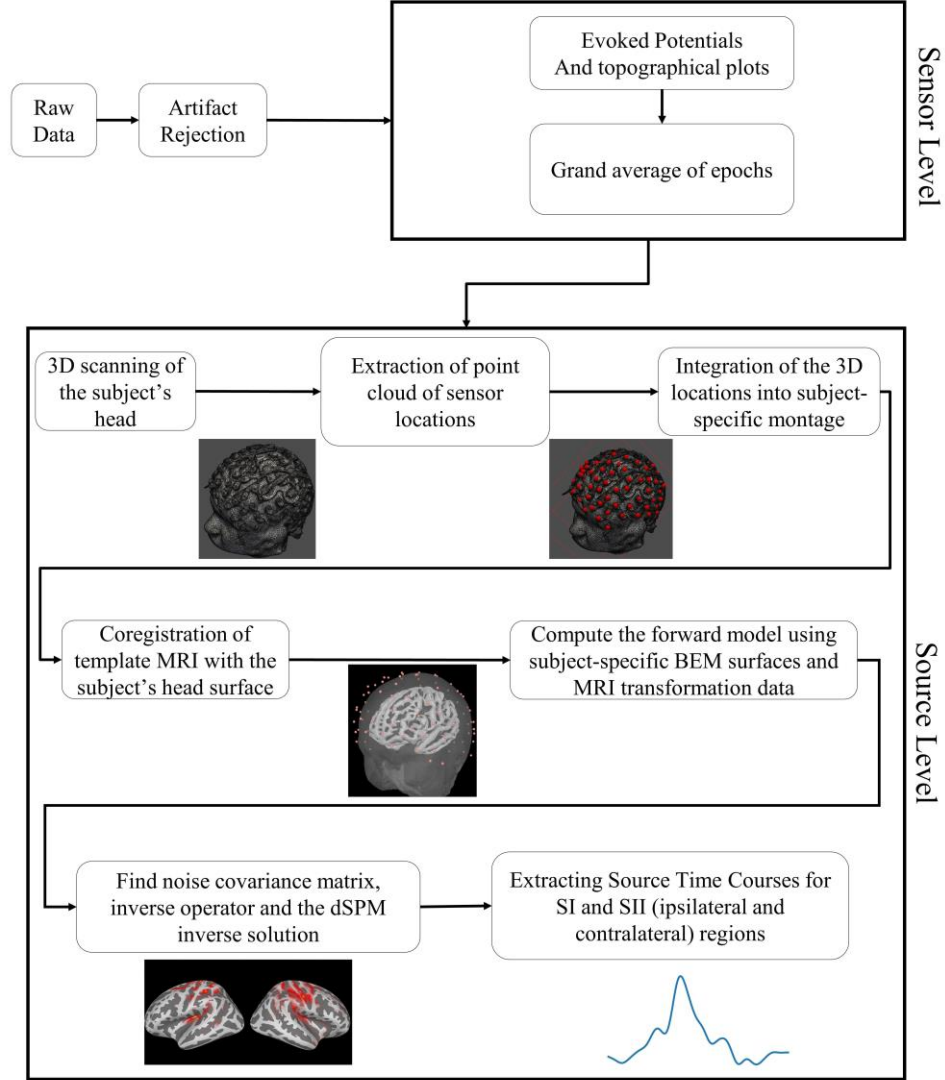
Fig. 2. The schematic diagram of the data analysis pipeline is shown. The raw data was pre-processed to remove the associated artifacts (EOG and ECG). The pre-processed EEG data was used to obtain the evoked responses (which consists of the sensor level analysis) which was then used to obtain the corresponding cortical activations (which consists of the source space analysis) in the a-priori ROIs. These cortical activations were further used in the statistical analysis (for more detailed information, see Section II. Methods).

C. Self-assessment manikin (SAM) for affect ratings

For the affect ratings, the self-assessment manikin (SAM) scale [34] was displayed on the screen. The SAM scale uses pictograms to depict degrees of Valence and Arousal and has been extensively u sed in exploratory affect studies [34]–[38] due to its ease of understanding. Valence and Arousal ratings were represented on a 9-point SAM scale, 1 being the lowest and 9 being the highest. For this study, the SAM scale representation used in [39] was adapted to acquire subjective ratings.

D. Stimulus delivery

For VBT stimulation, moving magnet linear actuators from Engineering Accoustics, Inc. were deployed viz. the C2 tactor (for delivering the high-frequency Stim 1) and the C2-HDLF tactor (for delivering the low-frequency Stim 2 and Stim 3), both having an equal area of stimulation of roughly 7cm^2. The tactors were attached to the locations with hypodermic tapes. The tactors were driven through dedicated APIs via a Visual C++ script capable of precisely controlling the amplitude, frequency and duration of stimulation alongside providing precise triggers for synchronizing data (See the data acquisition section).

E. Data acquisition

The g.Hiamp EEG amplifier (g.tec medical engineering GmbH) was used to record cortical electrophysiology. The subjects were mounted with a 118-channel wired g.GAMMAcap with g.SCARABEO active EEG electrodes.

Since EEG data often also carry noise induced by eye movements and heartbeats, in addition to the EEG channels, one ECG and two EOG (vertical and horizontal EOG) channels for artifact detection were deployed. The data was digitized at a sampling rate of 1200Hz.

The EEG set-up was driven via MATLAB with the help of dedicated Simulink libraries. To enable communication between the stimulus delivery unit and the data acquisition unit for time-synchronized operation, a virtual TCP/IP port was created. A trigger was sent to the MATLAB interface via the TCP/IP port every time a tactor was actuated from the VC++ script. The trigger information was recorded as time-series data in a separate trigger channel.

Apart from the cortical electrophysiology, a 3D model of the head surface of the subject wearing the EEG cap was scanned using a 3D scanner (Einscan pro+ Handheld 3D Scanner from Shining 3D). This was done to capture the precise sensor locations and the surface anatomy of the head.

F. Pre-processing

The data analysis pipeline is shown in Fig. 2. EEG data was analyzed with the MNE [40] package in Python. The montage (containing the subject-specific electrode locations obtained from the 3D scan) was applied to the raw data. A second-order Butterworth bandpass filter was used to limit the bandwidth of the data between 1 to 310Hz. The 50Hz line noise and its harmonics were removed with a notch filter. Bad channels and segments were manually rejected by visual inspection of the time series and the power spectrum density plots of the channels. The filtered EOG and ECG channels were then used to identify artifacts after decomposing the EEG signals using independent component analysis (ICA), which were then rejected. Additionally, the power spectrum of each ICA component was plotted to identify components of the electrical noise induced by the tactors and was subsequently removed. The resultant reconstructed data was re-inspected for any remaining bad segments of data which were rejected to get the clean pre-processed data.

G. Evoked responses

Average referencing was applied on the clean data which was then epoched using the trigger channel information with a pre-stimulus baseline of -200ms to -50ms. Each epoch consisted of a pre-stimulus interval (-200ms to 0s) which included the baseline, the stimulus duration (1s for Stim 1 and Stim 2, 50ms for Stim 3) and the inter-stimulus interval (1.5s for Stim 1 and Stim 2, 1s for Stim 3). The epoched data were baseline-corrected using the pre-stimulus interval of -200ms to -50ms followed by averaging across all trials to get the evoked response for each subject and condition. The evoked responses of all subjects were averaged across similar stimulation and location conditions to get 18 grand averaged evoked response data (for three stimulation conditions across six locations). The topological plots of the grand averaged evoked data were compared across the subject-wise evoked data to check for the consistency of responses across subjects. It was also used to arrive at time windows of interest for analyzing the cortical activity.

H. Source localisation

The evoked responses were further passed onto source analysis routines which require the anatomical information of the cortical structure, and the EEG sensor locations on the scalp to make estimates of cortical activity at different time points. For the same, Freesurfer's *fsaverage* was used as the template MRI for creating subject-specific MRIs. The source space of *fsaverage* consists of a grid of dipoles on the cortex with 3.1mm spacing between sources, resulting in 10242 sources per hemisphere. The source space was confined to the surface of the cortex, defined by the BEM. To obtain the pseudo-individual structural MRIs, the point cloud obtained from the 3D scan (using Einscan Pro+ Handheld 3D Scanner) of the subject's head surface was used to transform (affine) and fit the *fsaverage* MRI into the subject's head geometry. As a result, the point sources, the BEM and the scalp surface were scaled into a new model specific to the subject. This practice of applying pseudo-specific MRIs has been seen to reduce source localization errors as compared to directly using template MRIs.

After obtaining the subject-specific source spaces, electrical potentials were estimated at the scalp based on the activity of the individual source points defined in the transformed source space. This is known as the forward model. Forward modelling entailed the estimation of electrical potential at the scalp as a result of activity pertaining to the individual source points in the constructed source space, which in our case consisted of a total of 20484 source points.

For inverse modelling, we used dynamic statistical parametric mapping (dSPM) for inverse estimates, which allows for concurrent but spatially distributed dipoles. This was necessary as existing studies [25], [41] have shown the presence of multiple active sources during tactile stimulation. The epoched data was whitened using a regularized noise covariance matrix obtained from the baseline period of -200ms to -0.05ms. The depth-weighted inverse operator was computed with the help of the noise covariance matrix and the forward model and the inverse operators were obtained. The resulting spatiotemporal maps of statistically significant active sources were used to extract the averaged time courses of the sources for pre-stimulation, stimulation and interstimulus intervals. The source activations were rendered onto a common geometric space by projecting the individual source activities back into *fsaverage* such that they are comparable across subjects.

TABLE II
MIXED MODELS FOR THE ANALYSIS OF THE
BEHAVIORAL RATINGS

Dependent Variable → Factors ↓	Valence	Arousal
	Null model: Rating ~ 1 + (1|Subjects)	
Stimulus	Valence ~ Stimulus + (1|Subjects)	Arousal ~ Stimulus + (1|Subjects)
Location	Valence ~ Location + (1|Subjects)	Arousal ~ Location + (1|Subjects)
Location Type	Valence ~ Location Type + (1|Subjects)	Arousal ~ Location Type + (1|Subjects)

TABLE III
MIXED MODELS FOR THE ANALYSIS OF THE CORTICAL
MODULATIONS

Param → Factors ↓	N1				P2			
	SI_c	SI_i	SII_c	SII_i	SI_c	SI_i	SII_c	SII_i
	Null model: Param ~ 1 + (1|Subjects)							
Ratings								
Valence	Param ~ Valence + (1|Subjects)							
Arousal	Param ~ Arousal + (1|Subjects)							
Conditions								
Stimulus	Param ~ Stimulus + (1|Subjects)							
Location (all 6)	Param ~ Location + (1|Subjects)							
Location Type	Param ~ Location Type + (1|Subjects)							
Interactions								
Arousal:Location (all 6)	Param ~ Arousal:Location + (1|Subjects)							
Arousal:Location Type (G/NG)	Param ~ Arousal:Location Type + (1|Subjects)							
Arousal: timulus	Param ~ Arousal:Stimulus + (1|Subjects)							

I. Regions of interest (ROI) and Summary metrics

Bilateral post-central gyri (SI) and the supramarginal gyri (SII) were chosen as ROIs a-priori [42] and their corresponding source time courses (STCs) were computed. The N1 and P2 peaks occurring at 140 ± 21ms and 240 ± 12ms respectively (see section *Evoked responses)* for all 18 conditions (3 stimuli* 6 locations) were identified from the grand averaged evoked data. STCs specific to N1 and P2 activity were extracted by taking a window of ±30ms around the N1 and P2 peaks respectively. The mean of the source activities within these pre-defined windows specific to the 18 locations were used as the summary value of STCs across all subjects. Therefore, a total of 8 summary values (2 ROIs* 2 hemispheres* 2 Peaks) were obtained for each of the 18 conditions in all the subjects. The behavioral ratings were not further processed and were directly used as summary values. Along with the cortical modulations and behavioral ratings, experimental information (Location, Stimulus and Subject) was also included as summary values. The template of the summary metrics table is shown in Supplementary Material.

J. Statistical Analysis

The statistical analysis was performed in RStudio by the linear mixed models (LMM) approach using the *lmer* function from the *lme4* package [43]. We devised LMMs to test the fixed effects of the 1. Stimulus properties (*Stimulus*, *Location* and *Location Type*) on Ratings (*Arousal* and *Valence*) 2. Stimulus properties and *Ratings* on the cortical activity (N1 & P2 at four ROIs viz., ipsilateral and contralateral SI and SII). For assessing the effect of *Location Type*, stimulation sites were classified as 'glabrous' (index finger) or non-glabrous (Arm, Back, Abdomen, Leg, Toe) to assess the effect of *Location Type*. The subject-specific offset was included as the random effect. For each of the above, a parsimonious model was determined by comparing mixed-effects models (composed of fixed effects and random effects) with a *null* model (containing only the corresponding random effect). The model comparison was performed by ANOVA and $\alpha=0.05$ was used to evaluate the statistical significance of the results. Planned contrasts were devised using the *glht* function in the *multcomp* package and the post-hoc p-value adjustments

were done by Tukey's HSD. To control for multiple comparisons, the results were Bonferonni-corrected.

For the significant fixed effects variables, interactions were evaluated. The details of the model are shown in Table II and Table III.

K. Data Visualization

The evoked responses (see Fig. 5) obtained across all subjects and conditions were first grouped by the 18 conditions (6 locations* 3 stimuli). For each condition, a grand average across all subjects was obtained, leading to 18 such grand averaged evoked responses. and the data was plotted. The x and y axes limits were kept constant to make the plots comparable across time and amplitude respectively.

We also visualized the cortical effects pertaining to Valence and Arousal changes (see Fig. 6). Since Valence and Arousal are point scales, the STCs were grouped for better visualization, as explained below. The STCs were grouped into low and high based on an arbitrary threshold of 50% of the affect ratings (Rating <=5 was categorized as "Low" and >5 was categorized as "High"). A grand average of the grouped data was taken by separately applying this criterion on both scales. The resulting averaged STCs were subtracted to get an estimate of the cortical changes pertaining to the changes in valence or arousal ($Valence_{high}$ - $Valence_{low)}$ and $Arousal_{high}$ - $Arousal_{low}$). The subtracted data was then binned according to the time windows of interest (corresponding to N1 and P2) to get a single plot for N1 and P2 each. The averaged data was then z-score normalized, and a threshold at the critical value of 1.96 (representing a 95% confidence interval) was applied. The data was then plotted on the *fsaverage* inflated brain without thresholding.
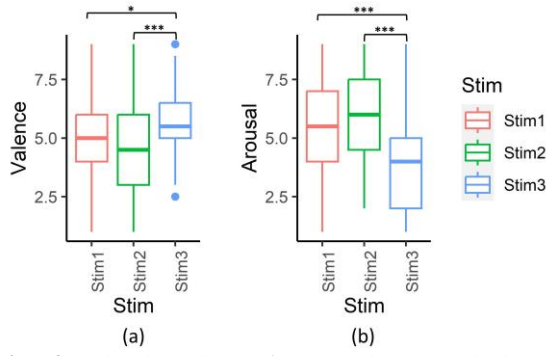
Fig. 3. The boxplots of (a) Valence and (b) Arousal ratings corresponding to the three different stimuli are shown. Stimulus had a significant main effect on both Valence (p=1.079e-05***) and Arousal (<2e-16***) along with the significant post hoc differences (for detailed information, see Table IV and Section III. A. Analysis of affect ratings).
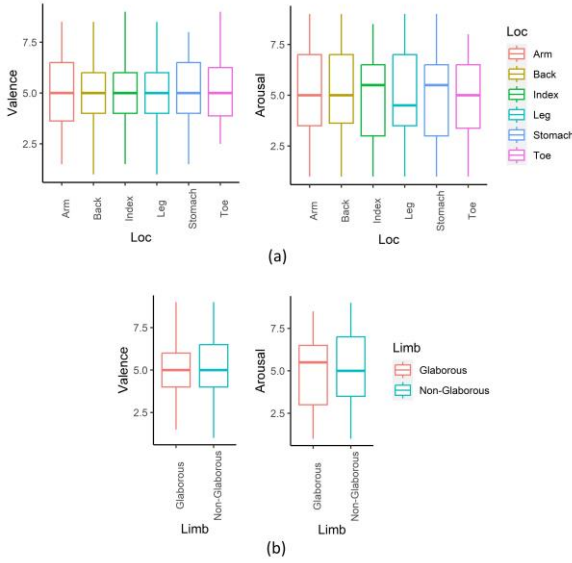

Fig. 4. The boxplots of (a) all six locations and (b) glabrous and non-glabrous locations are shown corresponding to the Valence and Arousal ratings. Location did not have a significant main effect on Valence (p=0.10) or Arousal (p=0.97). Similarly, Location Type did not have a significant main effect on Valence (p=0.92) or Arousal (p=0.78) either (for detailed information, see Table IV and Section III. A. Analysis of affect ratings).

III. RESULTS

A. Analysis of affect ratings

We investigated if (a) the different vibrotactile stimuli deployed in the study and (b) the different locations of stimulation were able to elicit a differential percept of affect responses. Therefore, *Valence* and *Arousal* ratings were individually tested against *Stimulus*, *Location* and *Location Type* as the modulating factors (fixed effects). Mixed model analysis revealed significant main effects of *Stimulus* on both

TABLE IV
RESULTS OF THE ANALYSIS OF BEHAVIORAL RATINGS

Dependent Variable → Factors ↓	Valence		Arousal	
	χ^2	p	χ^2	p
Stimulus	22.87	1.079e-05***	114.23	<2e-16***
Location	0.17	0.10	0.87	0.97
Location Type	0.0010	0.92	0.08	0.78
	Z	p	Z	p
Post-hoc (Stimulus)				
Stim2-Stim1	-1.47	0.14	1.86	0.06
Stim3-Stim1	2.40	0.03*	-8.51	<2e-16***
Stim3-Stim2	3.88	0.0003***	-10.39	<2e-16***

the rating scales, viz., *Valence* and *Arousal* (see Fig. 3 and Table IV). Post-hoc tests on the rating scales revealed that Stim 3 was rated significantly different than Stim 1 & 2 in both the rating scales. No significant difference could be observed between Stim 1 & 2 on either scale. No significant main effects of *Location* or *Location Type* were observed on the perceived ratings (see Fig. 4 and Table IV).

B. Evoked responses

Fig. 5 shows an overview of the time-locked evoked responses grand averaged in the time domain across all subjects. Consistent activations across all subjects at a latency of around 140ms post-stimulus were seen which lasted for around 100ms. Two peaks could be observed within this time frame, N1 occurring at 140 ± 21ms and P2 occurring at 240 ± 12ms. Across all conditions, at the onset of the evoked potentials, a rise in activation could be observed bilaterally in the post-central and parietal regions followed by a decline in the strength of the activations. Subsequently, a reversal could be noticed with strong activations in the frontal regions. Amplitude variations could be observed in the evoked potential plots for the different locations and stimuli.

C. Analysis of the cortical changes induced by affect

Next, we explored whether the perceptive differences are also reflected in the cortical electrophysiological changes elicited due to the stimuli, which can set the context for categorizing the cortical signatures to graded states of affect parameters. For the same, 8 cortical modulation parameters (2 ROIs * 2 hemispheres * 2 Peaks) as discussed earlier were individually treated as dependent variables and were tested across 5 different factors *(Valence, Arousal, Stimulus, Location* and *Location Type*. The results for the fitted models are listed in Table V.
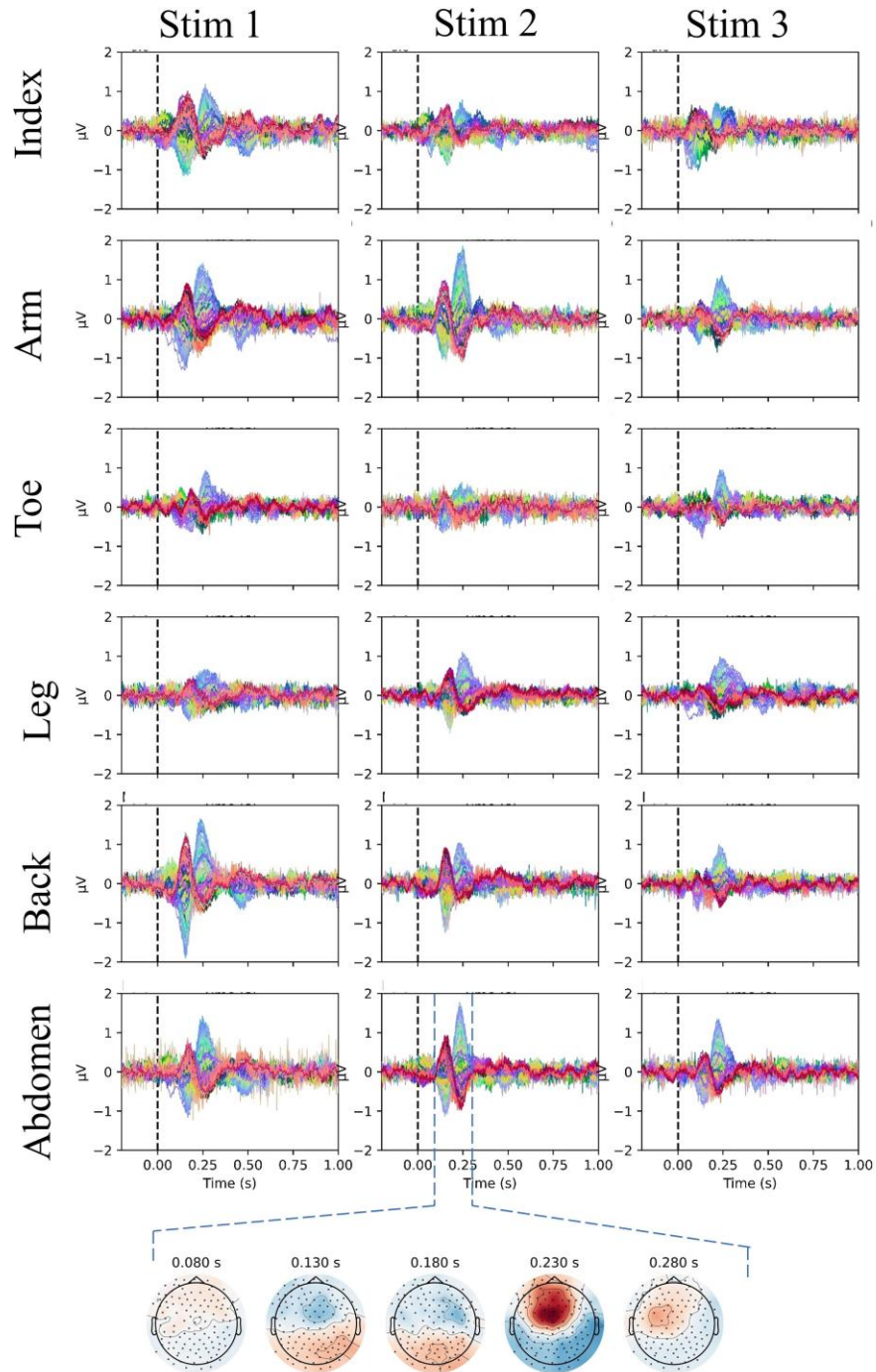
Fig. 5. This The evoked responses averaged across 200 trials and 19 subjects for each of the stimulation conditions and locations are shown. For comparison purposes, we show a time window of (-0.2, 1 s) to include the pre-stimulus interval and 1s post stimulus of the evoked potentials. The blue line indicates the onset of stimulus (at 0ms). Additionally, a representative topological plot of the evoked response in the Abdomen for Stim 2 is also shown for better visualization of the topological changes due to the cortical activations.

Significant main effect of *Arousal* were observed across all ROIs in both N1 and P2. No significant main effect of *Valence* was observed. The corresponding source activations are shown in Fig. 6. A significant main effect of *Location* could be observed in both N1 and P2 across all ROIs except ipsilateral SII in N1. A significant main effect of *Location Type* was observed across the contralateral SI and SII in N1. Significant effects of *Stimulus* were seen only in N1 in the

TABLE V

RESULTS FOR THE ANALYSIS OF CORTICAL MODULATION

Dependent Variable → Factors ↓	N1								P2							
	SI_c		SI_i		SII_c		SII_i		SI_c		SI_i		SII_c		SII_i	
	χ^2	p	χ^2	p	χ^2	p	χ^2	p	χ^2	p	χ^2	p	χ^2	p	χ^2	p
Ratings																
Valence	2.59	0.11	0.01	0.91	0.90	0.34	0.04	0.83	0.15	0.70	0.32	0.57	0.38	0.53	0.32	0.57
Arousal	8.06	0.004**	7.27	0.007**	9.39	0.002**	8.85	0.003**	11.37	0.0007***	7.11	0.008**	5.71	0.02*	13.11	0.0003***
Conditions																
Stimulus	7.70	0.02*	14.10	0.0008***	14.69	0.0006***	25.96	2.31e-06***	4.11	0.13	2.84	0.24	2.28	0.31	6.76	0.03*
Location (all 6)	26.75	6.37e-05***	12.45	0.03*	23.10	0.0003***	9.70	0.08	19.17	0.0002**	25.49	0.00011***	19.79	0.0013*	25.6	0.0001**
Location Type	13.48	0.0002***	0.24	0.62	14.54	0.0001***	0.10	0.76	0.80	0.37	1.96	0.16	0.12	0.73	1.49	0.22
Interactions																
Arousal : Stimulus	11.26	0.01*	18.01	0.0004***	16.93	0.0007***	27.50	4.63e-06***								0.002 **
Arousal : Location	30.33	3.41e-05***	21.93	0.001 **	27.21	0.0001***			36.49	2.22e-06***	37.33	1.52e-06***	32.33	1.41e-05***	45.13	4.40e-08***
Arousal : Location Type	16.97	0.0002***			19.44	5.99e-05***										

bilateral SI and SII. Since *Valence* did not have a main effect on the early cortical dynamics, we did not consider it for further analysis.

Significant interactions between *Arousal* and stimulation conditions *(Stimulus, Location, Location Type)* were observed across all ROIs for which the main effects of the stimulation conditions were significant (see Table V).

Additionally, we also combined the significant factors and their interactions to create mixed models with cortical activation as the dependent variable. Regression lines were plotted for the same and the coefficients of the model could be used for prediction of cortical activation pertaining to a specific location and arousal state and be used for possible applications. The models and results for the same are enlisted in the Supplementary Materials.
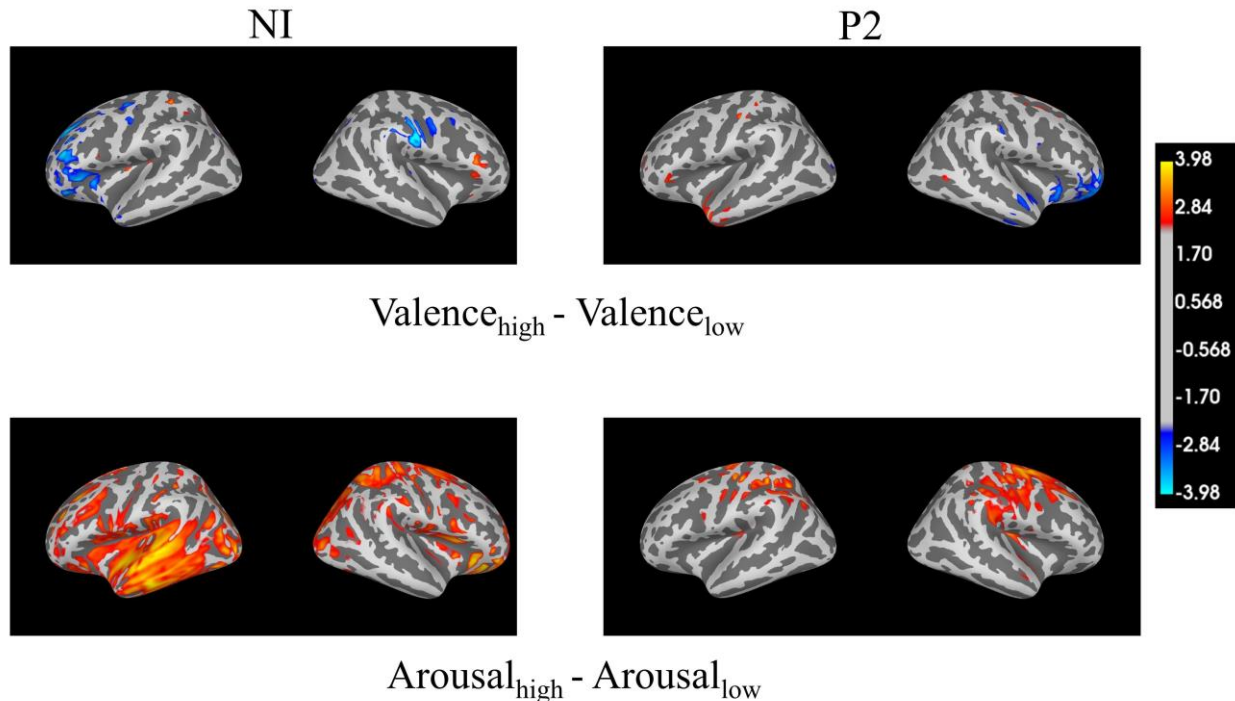
Fig. 6. The representative plots for cortical activations corresponding to high and low Valence, and high and low Arousal corresponding to N1 and P2 are shown. The source time courses feature ipsilateral and contralateral ROIs separately, with the N1 and P2 time durations marked with vertical markers. The corresponding N1 and P2 activations, morphed in the *fsaverage* are shown in an inflated brain.

IV. DISCUSSION

Our study is designed to address the following open questions in the field of affective haptics. Does the SCx encode aspects of the VBT-mediated affect? If so, do the nature and the location of stimulation play a deciding factor in eliciting reproducible levels of affect? Finally, can the behavioral responses be predicted with reasonably simple linear models with potential affective haptics applications in focus? To answer these, we designed three stimuli that have been shown to elicit differential affect responses and recorded the behavioral and electrocortical responses across six different locations.

We first analyzed the behavioral data to see if affect significantly varied across the different stimuli and locations. We found that the stimuli were able to elicit differential behavioral responses amongst the subjects. However, these responses did not seem to significantly vary across locations. Having established that the stimuli were able to induce differential affect, we next explored the cortical correlates of VBT to establish the corresponding relationships with the induced affect using mixed effects modelling.

We showed evoked responses with clear dipolar peaks time-locked to the VBT, in line with several existing studies [23], [44]. We then proceeded to obtain the corresponding source activations localized within the a-priori regions of the SCx to study the cortical changes pertaining to affect. We speculated

5 possible factors that could have contributed to cortical modulations in accordance with our paradigm, viz. *Valence, Arousal, Stimulus, Location and Location Type*. Hence, the role of these factors in modulating the source activity was correspondingly studied using mixed model analysis. We found that *Arousal, Stimulus, Location* and *Location Type* were the individual contributing factors in modulating the source activity while *Valence* did not show any significant effect. We next proceeded to investigate the interactions within the contributing factors to establish possible effects on the electrocortical signatures. It was found that *Arousal* had an interaction with all three stimulation conditions (*Location, Location Type and Stimulus*). Since the behavioral changes did not capture differences pertaining to Location, an interaction between *Arousal* and *Location* while cortical activation was a dependent factor suggests finer aspects of affect processing in the cortex that is uncaptured in the behavioral ratings which are more gross in nature.

With regard to these observations, we made several key inferences, as discussed below.

A. Percept of vibrotactile-mediated affect seems to be driven by the duration of the stimulus alone

We f ound that vibrotactile stimuli were able to elicit a differential percept of affect. Post-hoc tests showed that Stim 3 (f=60Hz, duration=50ms, ISI=1000s) was able to elicit differential affect ratings as compared to Stim 1 (f=300Hz, duration=1000ms, ISI=1500ms) and Stim 2 (f=60Hz,

duration=1000ms, ISI=1500ms) from the subjects, while Stim 1 and Stim 2 appeared to elicit similar affect ratings. Since Stim 3 greatly differs from Stim 1 and Stim 2 w.r.t its duration, we speculate that the duration of stimulation is the driving factor behind eliciting different Arousal levels. The duration of stimulation has been shown to directly influence the perceived amplitude of stimulation which in turn can be linked to Arousal levels.

An earlier study by Berglund and colleagues [45], was the first to show that the perceived amplitude of VBT shared a logarithmically increasing relationship with the stimulus duration. This effect is indicative of the theory of temporal integration that says that the information transfer is integrated over a period i.e. the resulting amplitude perception depends on a combination of the amplitude and duration of the stimulus pulse. Similar results were also replicated in [46]. Apart from VBT, this effect has been observed in other tactile modalities such as electrical stimulation [47] wherein, electrocutenous stimulation induced similar effects.

B. SI and SII mediated N1 and P2 encode Arousal but not Valence in the early stages of somatosensation

Our analysis revealed that only *Arousal* and not *Valence* had a main effect on the cortical activations in the SCx. Our findings on the vibrotactile modality have also been closely observed in the more natural tactile stimulation of brushing on the skin. The study [14] showed that when the subject's hand was stimulated by brushing, only intensity rating, which is analogous to Arousal rating [34], could be correlated with the BOLD response in the SCx and no correlations could be found with Valence ratings. Furthermore, on applying inhibitory rTMS to the SCx, only discriminatory aspects of touch could be modulated keeping the aspects related to affect intact.

A possible reason for this distinction can be found in the cortical pathways of mediating Valence and Arousal. It is known from the existing literature that Valence and Arousal are independently mediated by two separate cortical subsystems viz. the mesolimbic system and the reticular network [48] with other associated regions in the Valence and Arousal network depending on the modality of the stimuli such as visual stimuli [49]–[57], linguistic stimuli [58], odour [59], audio [60], [61] and taste [62]–[65]. The two networks subsequently converge in the prefrontal cortex [66], where information from both circuits is merged to form a collective percept of affect. While both the mesolimbic and reticular networks have ample back projections to the SCx [66], these effects might only be seen at later latencies rather than the N1 and P2, which are early potentials w.r.t VBT. However, since aspects of Arousal can be directly encoded by the perceived stimulus intensity, it is possible that the effect of Arousal seen in the early potent ials of N1 and P2 bypasses the reticular network altogether and reflect the tactile processing of stimulus intensity.

Some existing studies [28], [67]–[69] have shown the modulation of SCx with changes in the subject's affective state encompassing both Valence and Arousal. However, the modulatory input in such cases was visual or auditory stimuli delivered simultaneously with the tactile stimuli. Therefore, it is likely that any changes in the SCx may not be attributed to the change in somatosensory stimulation and were related to the affect component induced by the stimuli it was applied in conjunction with. Our study, on the other hand, does not employ any other concurrent stimuli. It therefore portrays the changes in the SCx purely due to the affect component induced by somatosensory stimuli, without the influence of other modalities of stimulation such as auditory or visual stimuli.

C. The glabrous nature of the site of stimulation does not play a role in modulating the perceptual aspects of vibrotactile-mediated affect

From the behavioral results (see Table IV), we observed that the *Valence* and *Arousal* did not significantly change with the different stimulation locations.

Existing literature shows that natural touch that induces affect, such as stroking, brushing and gentle pressure, is relayed more by the non-glabrous skin (that is innervated by the C-tactile fibers at the end of hair follicles) to the cortex. The glabrous skin (classically known to be devoid of C-tactile fibers) is known to contribute more towards the discriminatory touch. However, recent studies have also shown that tactile response is multimodal in nature wherein the C-tactile fibers have been shown to respond to VBT. Given this, we had earlier speculated that if the affect mediation due to VBT is similar to that of natural touch, then this effect would be visible as differential processing of affect between the glabrous and non-glabrous locations. Therefore, we additionally studied the effect of *Location* on the *Arousal* by grouping them into glabrous and non-glabrous sites. We then performed tests to check if vibrotactile-mediated affect was differentially elicited across these sites. However, no such distinction could be made, indicating that glabrous and non-glabrous skin behave alike in mediating vibrotactile-based affect.

In studies involving the more natural forms of touch such as fabrics, a distinct difference in response can be seen across locations for the same type of stimulus. [1], [2] deployed differently textured materials at different velocities across the arm and the face (both non-glabrous in nature) and found significant changes in the subjective pleasant ratings across the locations and velocities. Another study [70] conducted a similar experiment where stimuli were deployed across glabrous and non-glabrous locations. Pleasantness ratings were found to be lesser in the glabrous sites as compared to the non-glabrous sites. Differentiated effects on pleasantness as well as the cortical correlates for glabrous and non-glabrous skin were likewise found in [5]. Since the behavioral responses of VBT-mediated affect do not demonstrate similar differentiations across locations, we can infer that VBT-mediated affect processing differs from that of natural touch and uses different functional pathways. While Arousal, being a gross scale can capture location-based differences in more natural forms of touch, the same may not be possible with VBT.

D. The location of stimulation plays a role in modulating the cortical aspects of vibrotactile affect

The analysis of interactions between *Arousal, Location* and *Location Type* in modulating the cortical activity revealed

significant effects (see Table V) indicating that Location does play a role when the cortical changes encoding Arousal are considered. However, the effect of *Location* was not seen on the behavioral ratings of Arousal. Arousal is a gross scale that may not have captured the finer changes perceived by the subjects pertaining to VBT-induced affect. Therefore, even though the location of stimulation may not play a major role in the gross perceptual aspects of VBT-induced affect, differential cortical modulation needs to be factored in while implementing neurofeedback-based affective haptics technology.

E. Limitations

Our study is not without limitations. Our study indicates the importance of duration in modulating affect. However, our limited duration settings (only two settings, i.e. 50ms and 1000ms) prevented us from exploring the possibility of a non-linear relationship between subject ratings and the duration. Therefore, a broader range of duration needs to be implemented to unveil the finer aspects of behavioral processing. In addition to this, while our stimuli choice of 300Hz could optimally excite the Pacinian Corpuscles [71], [72], 60Hz was at the extreme end of the frequency spectrum known to elicit Meissner's corpuscles. Therefore, to study the differential effects of sensory receptors on affect, a broader frequency spectrum needs to be considered. Furthermore, keeping in mind there are huge inter-subject variabilities [73] in experiencing affect, it may be judicious to have subject-wise trials with a large number of data across locations per subject, that will enable a subject-specific analysis.

E. Future scope

Our study contributes towards a more systematic analysis of VBT-induced affect. Our study draws insights into how the "atomistic attributes" of VBT induce affect. These can be used to create a wider range of complex VBT stimuli that mimic more natural VBT patterns and interpret results. In conjunction with showing that behavioral ratings have a relationship with the early cortical potentials, our study establishes the groundwork for treating the relationship between cortical modulation, behavioral ratings and stimulation parameters as reasonably simple linear models. This can be highly useful whilst designing relatively simple, cost-effective implementations of day-to-day real-time wearable haptic devices inducing affect. Our results show that Location does not independently influence Arousal. However, an interaction between Location and Arousal is observed when analyzing the cortical changes. This highlights the complexity of neural processing related to affective perception and cortical modulation and warrants further investigations.

Our research findings have several implications. Utilizing the knowledge of the role of stimulation duration in modulating affect can assist in stimulus optimization in affective haptic interfaces. It can help develop personalized interfaces tailored to specific user needs, therefore enhancing user engagement and satisfaction in applications such as virtual reality, gaming, and rehabilitation.

REFERENCES

[1] G. K. Essick, A. James, and F. P. McGlone, "Psychophysical assessment of the affective components of non-painful touch," *NeuroReport*, vol. 10, no. 10, pp. 2083–2087, 1999, doi: 10.1097/00001756-199907130-00017.

[2] G. K. Essick *et al.*, "Quantitative assessment of pleasant touch," *Neuroscience and Biobehavioral Reviews*, vol. 34, no. 2, pp. 192–203, 2010, doi: 10.1016/j.neubiorev.2009.02.003.

[3] A. Greco, A. Guidi, M. Bianchi, A. Lanata, G. Valenza, and E. P. Scilingo, "Brain Dynamics Induced by Pleasant/Unpleasant Tactile Stimuli Conveyed by Different Fabrics," *IEEE Journal of Biomedical and Health Informatics*, vol. 23, no. 6, pp. 2417–2427, 2019, doi: 10.1109/JBHI.2019.2893324.

[4] M. Nardelli, A. Greco, M. Bianchi, E. P. Scilingo, and G. Valenza, "On the pleasantness of a haptic stimulation: How different textures can be recognized through heart rate variability nonlinear analysis," *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS*, vol. 2016-Octob, pp. 3560–3563, 2016, doi: 10.1109/EMBC.2016.7591497.

[5] D. Hoefer, M. Handel, K. M. Müller, and T. R. Hammer, "Electroencephalographic study showing that tactile stimulation by fabrics of different qualities elicit graded event-related potentials," *Skin Research and Technology*, vol. 22, no. 4, pp. 470–478, 2016, doi: 10.1111/srt.12288.

[6] M. von Mohr, M. J. Crowley, J. Walthall, L. C. Mayes, K. A. Pelphrey, and H. J. V. Rutherford, "EEG captures affective touch: CT-optimal touch and neural oscillations," *Cognitive, Affective and Behavioral Neuroscience*, vol. 18, no. 1, pp. 155–166, 2018, doi: 10.3758/s13415-017-0560-6.

[7] L. S. Löken, J. Wessberg, I. Morrison, F. McGlone, and H. Olausson, "Coding of pleasant touch by unmyelinated afferents in humans," *Nature Neuroscience*, vol. 12, no. 5, pp. 547–548, 2009, doi: 10.1038/nn.2312.

[8] I. Gordon, A. C. Voos, R. H. Bennett, D. Z. Bolling, K. A. Pelphrey, and M. D. Kaiser, "Brain mechanisms for processing affective touch," *Human Brain Mapping*, vol. 34, no. 4, pp. 914–922, 2013, doi: 10.1002/hbm.21480.

[9] M. Davidovic, G. Starck, and H. Olausson, "Processing of affective and emotionally neutral tactile stimuli in the insular cortex," *Developmental Cognitive Neuroscience*, vol. 35, no. November, pp. 94–103, 2019, doi: 10.1016/j.dcn.2017.12.006.

[10] R. Pawling, P. R. Cannon, F. P. McGlone, and S. C. Walker, "C-tactile afferent stimulating touch carries a positive affective value," *PLoS ONE*, vol. 12, no. 3, pp. 1–15, 2017, doi: 10.1371/journal.pone.0173457.

[11] R. Ackerley, I. Carlsson, H. Wester, H. Olausson, and H. Backlund Wasling, "Touch perceptions across skin sites: Differences between sensitivity, direction discrimination and pleasantness," *Frontiers in Behavioral Neuroscience*, vol. 8, no. FEB, pp. 1–10, 2014, doi: 10.3389/fnbeh.2014.00054.

[12] G. Corniani and H. P. Saal, "Tactile innervation densities across the whole body," *Journal of Neurophysiology*, vol. 124, no. 4, pp. 1229–1240, 2020, doi: 10.1152/jn.00313.2020.

[13] H. Culbertson, S. B. Schorr, and A. M. Okamura, "Haptics: The Present and Future of Artificial Touch Sensation," *Annual Review of Control, Robotics, and Autonomous Systems*, vol. 1, no. March, pp. 385–409, 2018, doi: 10.1146/annurev-control-060117-105043.

[14] L. K. Case, C. M. Laubacher, H. Olausson, B. Wang, P. A. Spagnolo, and M. C. Bushnell, "Encoding of touch intensity but not pleasantness in human primary somatosensory cortex," *Journal of Neuroscience*, vol. 36, no. 21, pp. 5850–5860, 2016, doi: 10.1523/JNEUROSCI.1130-15.2016.

[15] Å. Vallbo, H. Olausson, J. Wessberg, and U. Norrsell, "A system of unmyelinated afferents for innocuous mechanoreception in the human skin," *Brain Research*, vol. 628, no. 1–2, pp. 301–304, 1993,

doi: 10.1016/0006-8993(93)90968-S.

[16] Y. Yoo, T. Yoo, J. Kong, and S. Choi, "Emotional responses of tactile icons: Effects of amplitude, frequency, duration, and envelope," *IEEE World Haptics Conference, WHC 2015*, pp. 235–240, 2015, doi: 10.1109/WHC.2015.7177719.

[17] H. Hasegawa, S. Okamoto, K. Ito, and Y. Yamada, "Affective Vibrotactile Stimuli: Relation between Vibrotactile Parameters and Affective Responses," *International Journal of Affective Engineering*, vol. 18, no. 4, pp. 171–180, 2019, doi: 10.5057/ijae.ijae-d-18-00008.

[18] J. A. Russell, "A circumplex model of affect," *Journal of Personality and Social Psychology*, vol. 39, no. 6, pp. 1161–1178, 1980, doi: 10.1037/h0077714.

[19] G. Valenza, A. Greco, M. Bianchi, M. Nardelli, S. Rossi, and E. P. Scilingo, "EEG oscillations during caress-like affective haptic elicitation," *Psychophysiology*, vol. 55, no. 10, pp. 1–15, 2018, doi: 10.1111/psyp.13199.

[20] H. Singh *et al.*, "The brain's response to pleasant touch: An EEG investigation of tactile caressing," *Frontiers in Human Neuroscience*, vol. 8, no. November, pp. 1–10, 2014, doi: 10.3389/fnhum.2014.00893.

[21] C. Mccabe, E. T. Rolls, A. Bilderbeck, and F. McGlone, "Cognitive influences on the affective representation of touch and the sight of touch in the human brain," *Social Cognitive and Affective Neuroscience*, vol. 3, no. 2, pp. 97–108, 2008, doi: 10.1093/scan/nsn005.

[22] T. Allison, G. McCarthy, C. C. Wood, P. D. Williamson, and D. D. Spencer, "Human cortical potentials evoked by stimulation of the median nerve. II. Cytoarchitectonic areas generating long-latency activity," *Journal of Neurophysiology*, vol. 62, no. 3, pp. 711–722, 1989, doi: 10.1152/jn.1989.62.3.711.

[23] H. Hämäläinen, J. Kekoni, M. Sams, K. Reinikainen, and R. Näätänen, "Human somatosensory evoked potentials to mechanical pulses and vibration: contributions of SI and SII somatosensory cortices to P50 and P100 components," *Electroencephalography and Clinical Neurophysiology*, vol. 75, no. 1–2, pp. 13–21, 1990, doi: 10.1016/0013-4694(90)90148-D.

[24] C. Simões, O. Jensen, L. Parkkonen, and R. Hari, "Phase locking between human primary and secondary somatosensory cortices.," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 100, no. 5, pp. 2691–2694, 2003, doi: 10.1073/pnas.0437944100.

[25] C. Simões, M. Mertens, N. Forss, V. Jousmäki, B. Lütkenhöner, and R. Hari, "Functional overlap of finger representations in human SI and SII cortices," *Journal of Neurophysiology*, vol. 86, no. 4, pp. 1661–1665, 2001, doi: 10.1152/jn.2001.86.4.1661.

[26] T. Hansson and T. Brismar, "Tactile stimulation of the hand causes bilateral cortical activation: A functional magnetic resonance study in humans," *Neuroscience Letters*, vol. 271, no. 1, pp. 29–32, 1999, doi: 10.1016/S0304-3940(99)00508-X.

[27] D. Cheyne *et al.*, "Neuromagnetic imaging of cortical oscillations accompanying tactile stimulation," *Cognitive Brain Research*, vol. 17, no. 3, pp. 599–611, 2003, doi: 10.1016/S0926-6410(03)00173-3.

[28] N. Ravaja, V. Harjunen, I. Ahmed, G. Jacucci, and M. M. Spapé, "Feeling Touched: Emotional Modulation of Somatosensory Potentials to Interpersonal Touch," *Scientific Reports*, vol. 7, no. March 2016, pp. 1–11, 2017, doi: 10.1038/srep40504.

[29] A. Mazza *et al.*, "Hedonic and autonomic responses in promoting affective touch," *Scientific reports*, vol. 13, no. 1, p. 11201, 2023, doi: 10.1038/s41598-023-37471-9.

[30] Y. Takatsuru and N. Koibuchi, "Alteration of somatosensory response in adulthood by early life stress," *Frontiers in Molecular Neuroscience*, vol. 8, no. MAY, pp. 1–7, 2015, doi: 10.3389/fnmol.2015.00015.

[31] D. Ray, D. Bezmaternykh, M. Mel'nikov, K. J. Friston, and M. Das, "Altered effective connectivity in sensorimotor cortices is a signature of severity and clinical course in depression," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 118, no. 40, 2021, doi: 10.1073/pnas.2105730118.

[32] L. Kang *et al.*, "Functional connectivity between the thalamus and the primary somatosensory cortex in major depressive disorder: A resting-state fMRI study," *BMC Psychiatry*, vol. 18, no. 1, pp. 4–11, 2018, doi: 10.1186/s12888-018-1913-6.

[33] L. Minuzzi, S. K. Syan, M. Smith, A. Hall, G. B. C. Hall, and B. N. Frey, "Structural and functional changes in the somatosensory cortex in euthymic females with bipolar disorder," *Australian and New Zealand Journal of Psychiatry*, vol. 52, no. 11, pp. 1075–1083, 2018, doi: 10.1177/0004867417746001.

[34] M. M. Bradley and P. J. Lang, "Measuring emotion: The self-assessment manikin and the semantic differential," *Journal of Behavior Therapy and Experimental Psychiatry*, vol. 25, no. 1, pp. 49–59, 1994, doi: 10.1016/0005-7916(94)90063-9.

[35] A. Betella and P. F. M. J. Verschure, "The affective slider: A digital self-assessment scale for the measurement of human emotions," *PLoS ONE*, vol. 11, no. 2, pp. 1–11, 2016, doi: 10.1371/journal.pone.0148037.

[36] T. Xie, M. Cao, and Z. Pan, "Applying Self-Assessment Manikin (SAM) to Evaluate the Affective Arousal Effects of VR Games," *ACM International Conference Proceeding Series*, pp. 134–138, 2020, doi: 10.1145/3383812.3383844.

[37] C. Sainz-de-Baranda Andujar, L. Gutiérrez-Martín, J. Á. Miranda-Calero, M. Blanco-Ruiz, and C. López-Ongil, "Gender biases in the training methods of affective computing: Redesign and validation of the Self-Assessment Manikin in measuring emotions via audiovisual clips," *Frontiers in Psychology*, vol. 13, no. October, pp. 1–16, 2022, doi: 10.3389/fpsyg.2022.955530.

[38] K. K. Imbir, J. Duda-Goławska, A. Sobieszek, A. Wielgopolan, M. Pastwa, and J. Żygierewicz, "Arousal, subjective significance and the origin of valence aligned words in the processing of an emotional categorisation task," *PLoS ONE*, vol. 17, no. 3 March, pp. 1–27, 2022, doi: 10.1371/journal.pone.0265537.

[39] S. J. E. Langeslag, "Effects of organization and disorganization on pleasantness, calmness, and the frontal negativity in the event-related potential," *PLoS ONE*, vol. 13, no. 8, pp. 1–13, 2018, doi: 10.1371/journal.pone.0202726.

[40] A. Gramfort *et al.*, "MEG and EEG data analysis with MNE-Python," *Frontiers in Neuroscience*, vol. 7, no. 7 DEC, pp. 1–13, 2013, doi: 10.3389/fnins.2013.00267.

[41] V. Jousmäki and R. Hari, "Somatosensory evoked fields to large-area vibrotactile stimuli," *Clinical Neurophysiology*, vol. 110, no. 5, pp. 905–909, 1999, doi: 10.1016/S1388-2457(98)00059-5.

[42] J. Kim, Y. G. Chung, S. C. Chung, H. H. Bulthoff, and S. P. Kim, "Neural Categorization of Vibrotactile Frequency in Flutter and Vibration Stimulations: An fMRI Study," *IEEE Transactions on Haptics*, vol. 9, no. 4, pp. 455–464, 2016, doi: 10.1109/TOH.2016.2593727.

[43] B. Winter, "Linear models and linear mixed effects models in R with linguistic applications," no. Tutorial 2, pp. 1–22, 2013, [Online]. Available: http://arxiv.org/abs/1308.5499

[44] R. Hari, "Evoked potentials elicited by long vibrotactile stimuli in the human EEG," *Pflügers Archiv European Journal of Physiology*, vol. 384, no. 2, pp. 167–170, 1980, doi: 10.1007/BF00584434.

[45] B. Berglund, U. Berglund, and G. Ekman, "Temporal Integration of Vibrotactile Stimulation," *Perceptual and Motor Skills*, vol. 25, no. 2, pp. 549–560, Oct. 1967, doi: 10.2466/pms.1967.25.2.549.

[46] G. Ekman, M. Frankenhaeuser, B. Berglund, and M. Waszak, "Apparent duration as a function of intensity of vibrotactile stimulation.," *Perceptual and motor skills*, vol. 28, no. 1, pp. 151–156, 1969, doi: 10.2466/pms.1969.28.1.151.

[47] E. L. Graczyk, M. A. Schiefer, H. P. Saal, B. P. Delhaye, S. J. Bensmaia, and D. J. Tyler, "The neural basis of perceived intensity in natural and artificial touch," *Science Translational Medicine*, vol. 8, no. 362, pp. 1–11, 2016, doi: 10.1126/scitranslmed.aaf5187.

[48] J. Posner and J. A. Russell, "The circumplex model of affect : An integrative approach to affective neuroscience , cognitive development , and psychopathology," pp. 715–734, 2017.

[49] S. Anders, M. Lotze, M. Erb, W. Grodd, and N. Birbaumer, "Brain activity underlying emotional valence and arousal: A response-related fMRI study," *Human Brain Mapping*, vol. 23, no. 4, pp. 200–209, 2004, doi: 10.1002/hbm.20048.

[50] A. Greco, G. Valenza, and E. P. Scilingo, "Brain Dynamics during Arousal-Dependent Pleasant/Unpleasant Visual Elicitation: An Electroencephalographic Study on the Circumplex Model of Affect," *IEEE Transactions on Affective Computing*, vol. 12, no. 2, pp. 417–428, 2021, doi: 10.1109/TAFFC.2018.2879343.

[51] J. O. Doherty, J. Winston, H. Critchley, D. Perrett, D. M. Burt, and R. J. Dolan, "Beauty in a smile : the role of medial orbitofrontal cortex in facial attractiveness," vol. 41, pp. 147–155, 2003.

[52] S. Jorge, V. Michel, B. Thirion, and M. Pessiglione, "Article An Automatic Valuation System in the Human Brain : Evidence from Functional Neuroimaging," no. Figure 1, pp. 431–439, 2009, doi: 10.1016/j.neuron.2009.09.040.

[53] T. Tsukiura and R. Cabeza, "Shared brain activity for aesthetic and moral judgments : implications for the Beauty-is-Good stereotype," pp. 138–148, 2011, doi: 10.1093/scan/nsq025.

[54] G. Iaria, C. J. Fox, C. T. Waite, I. Aharon, and J. J. S. Barton, "THE CONTRIBUTION OF THE FUSIFORM GYRUS AND SUPERIOR TEMPORAL SULCUS IN PROCESSING FACIAL ATTRACTIVENESS : NEUROPSYCHOLOGICAL AND NEUROIMAGING EVIDENCE," vol. 155, pp. 409–422, 2008, doi: 10.1016/j.neuroscience.2008.05.046.

[55] A. Heinzel *et al.*, "How do we modulate our emotions ? Parametric fMRI reveals cortical midline structures as regions specifically involved in the processing of emotional valences," vol. 25, pp. 348–358, 2005, doi: 10.1016/j.cogbrainres.2005.06.009.

[56] U. Kirk, "The neural basis of object-context relationships on aesthetic judgment," *PLoS ONE*, vol. 3, no. 11, 2008, doi: 10.1371/journal.pone.0003754.

[57] A. Chatterjee, A. Thomas, S. E. Smith, and G. K. Aguirre, "The Neural Response to Facial Attractiveness," *Neuropsychology*, vol. 23, no. 2, pp. 135–143, 2009, doi: 10.1037/a0014430.

[58] T. Colibazzi *et al.*, "Neural Systems Subserving Valence and Arousal During the Experience of Induced Emotions," *Emotion*, vol. 10, no. 3, pp. 377–389, 2010, doi: 10.1037/a0018484.

[59] F. Grabenhorst, E. T. Rolls, C. Margot, M. A. A. P. Silva, and M. I. Velazco, "How Pleasant and Unpleasant Stimuli Combine in Different Brain Regions : Odor Mixtures," vol. 27, no. 49, pp. 13532–13540, 2007, doi: 10.1523/JNEUROSCI.3337-07.2007.

[60] A. J. Blood, R. J. Zatorre, P. Bermudez, and A. C. Evans, "Emotional responses to pleasant and unpleasant music correlate with activity in paralimbic brain regions," vol. 2, no. 4, 1999.

[61] K. Kornysheva, D. Y. Von Cramon, and T. Jacobsen, "Tuning-in to the Beat : Aesthetic Appreciation of Musical Rhythms Correlates with a Premotor Activity Boost," vol. 64, pp. 48–64, 2010, doi: 10.1002/hbm.20844.

[62] J. P. O. Doherty, T. W. Buchanan, B. Seymour, and R. J. Dolan, "Predictive Neural Coding of Reward Preference Involves Dissociable Responses in Human Ventral Midbrain and Ventral Striatum," pp. 157–166, 2006, doi: 10.1016/j.neuron.2005.11.014.

[63] F. Grabenhorst and E. T. Rolls, "Selective attention to affective value alters how the brain processes taste stimuli," vol. 27, pp. 723–729, 2008, doi: 10.1111/j.1460-9568.2008.06033.x.

[64] I. E. T. De Araujo, E. T. Rolls, M. L. Kringelbach, F. McGlone, and N. Phillips, "Taste-olfactory convergence, and the representation of the pleasantness of flavour, in the human brain," *European Journal of Neuroscience*, vol. 18, no. 7, pp. 2059–2068, 2003, doi: 10.1046/j.1460-9568.2003.02915.x.

[65] F. Grabenhorst, E. T. Rolls, B. A. Parris, and A. A. D'Souza, "How the brain represents the reward value of fat in the mouth," *Cerebral Cortex*, vol. 20, no. 5, pp. 1082–1091, 2010, doi: 10.1093/cercor/bhp169.

[66] J. Posner, J. A. Russell, and B. S. Peterson, "The circumplex model of affect: An integrative approach to affective," *Dev Psychopathol*, vol. 141, no. 4, pp. 520–529, 2005.

[67] V. Gazzola, M. L. Spezio, J. A. Etzel, F. Castelli, R. Adolphs, and C. Keysers, "Primary somatosensory cortex discriminates affective significance in social touch," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 109, no. 25, pp. 1657–1666, 2012, doi: 10.1073/pnas.1113211109.

[68] Y. Tsalamlal, M. A. Amorim, J. C. Martin, and M. Ammi, "Modeling emotional valence integration from voice and touch," *Frontiers in Psychology*, vol. 9, no. OCT, pp. 1–16, 2018, doi: 10.3389/fpsyg.2018.01966.

[69] N. Bolognini, A. Rossetti, S. Convento, and G. Vallar, "Understanding others' feelings: The role of the right primary somatosensory cortex in encoding the affective valence of others' touch," *Journal of Neuroscience*, vol. 33, no. 9, pp. 4201–4205, 2013, doi: 10.1523/JNEUROSCI.4498-12.2013.

[70] R. Etzi, C. Spence, and A. Gallace, "Textures that we like to touch: An experimental study of aesthetic preferences for tactile stimuli," *Consciousness and Cognition*, vol. 29, pp. 178–188, 2014, doi: 10.1016/j.concog.2014.08.011.

[71] S. J. Bolanowski and J. J. Zwislocki, "Intensity and frequency characteristics of pacinian corpuscles. II. Receptor potentials," *Journal of Neurophysiology*, vol. 51, no. 4, pp. 812–830, 1984, doi: 10.1152/jn.1984.51.4.812.

[72] J. Bell, S. Bolanowski, and M. H. Holmes, "The structure and function of pacinian corpuscles: A review," *Progress in Neurobiology*, vol. 42, no. 1, pp. 79–128, 1994, doi: 10.1016/0301-0082(94)90022-1.

[73] M. Hollins and E. A. Roy, "Perceived intensity of vibrotactile stimuli: The role of mechanoreceptive channels," *Somatosensory and Motor Research*, vol. 13, no. 3–4, pp. 273–286, 1996, doi: 10.3109/08990229609052583.

Suranjita Ganguly received the B.Tech degree from Kalinga Institute of Industrial Technology, Odisha, India in 2015 and M.Tech degree from Dr. B. R. Ambedkar National Institute of Technology, Jalandhar, India in 2019. She is currently pursuing her doctoral degree from the Indian Institute of Technology, Hyderabad, India. She is the recipient of the Prime Minister's Research Fellows Award. Her research interests include affective computing, affective haptics, virtual reality, and affective neuroscience.

Aditya Koppula received the MBBS degree from Osmania medical college, Hyderabad, India in 2010 and M.D (Physiology) degree from Osmania medical college, Hyderabad, India in 2016. He received University medal for the best outgoing student in Physiology. He submitted his PhD thesis at the Indian Institute of Technology, Hyderabad, India, in January 2023. He is currently working as Assistant Professor of Physiology, Apollo Institute of Medical Sciences and Research Hyderabad. His research interests include sensorimotor neuroscience in health and motor disorders, cardiorespiratory coupling, and systems physiology.

Kousik Sarathy Sridharan is currently Assistant Professor at the Dept. of Biomedical Engineering at the Indian Institute of Technology, Hyderabad, India. He obtained his PhD degree in Neuroscience from Aarhus University, Aarhus, Denmark. His work spans the areas of functional neuroimaging, neurorehabilitation, and affective haptics.