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Identification of the hemodynamic correlates of basic emotional states with a mobile functional near infrared spectroscopy system

Temel Duygusal Durumların Hemodinamik Karşılıklarının Taşınabilir bir İşlevsel Yakın Kızılaltı Spektroskopi Sistemi ile Tanımlanması

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ABSTRACT

Aim: The aim of this study was to evaluate the feasibility of a functional near infrared spectroscopy (fNIRS) system, for quantification of the similarities and differences in the spatial localization of cerebral hemodynamic activation, induced by visual presentation of neutral, negative and positive valence emotional stimuli.
Method: Thirteen healthy subjects viewed neutral, pleasant and unpleasant pictures from the International Affective Picture System (IAPS) database in a block design experiment while the prefrontal cortical hemodynamic changes induced by emotional stimuli were continuously recorded with a 20 channel fNIRS system that covered the forehead region.
Results: Negative valence pictures induced higher hemodynamic activity in right lateralized regions involving dorsolateral and orbitofrontal cortex, when compared to neutral and positive valence stimuli (pFDR<0.05). Each stimulus condition induced a distinct cortical activation pattern that could be identified with fNIRS.
Conclusion: Our findings support the notion that different basic emotions have distinct localization and separable hemodynamic correlates in the prefrontal cortex region, which can be detected with a mobile fNIRS system. The distinct cortical hemodynamic activity patterns associated with each emotional state show the potential of fNIRS technology for decoding and differentiating basic emotions objectively and real time for future clinical and daily life applications.

Keywords: Functional near infrared spectroscopy, brain computer interface, prefrontal cortex, emotional valence

ÖZ

Amaç: Bu çalışmanın amacı, bir işlevsel yakın kızılaltı spektroskopi (İYKAS) sisteminin nötral, olumsuz ve olumlu değerlikli duygusal uyarıların sebep oldukları beyin hemodinamik etkinliklerinin uzamsal yerleşimlerindeki benzerlik ve farklılıkları niceliklendirmedeki uygunluğunu test etmektir.
Yöntemler: 13 sağlıklı denek, Uluslararası Duygusal Resim Sistemi (IAPS) veritabanından alınan nötral, hoşa giden ve hoşa gitmeyen içerikli resimleri blok bir deney tasarımı içerisinde izlerlerken, duygusal uyaranların sebep olduğu prefrontal kortikal hemodinamik değişimler alın bölgesine yerleştirilen 20 kanallı bir İYKAS sistemi ile ölçüldü.
Bulgular: Olumsuz değerlikli resimler dorsolateral ve orbitofrontal korteksi kapsayan sağ lateral bölgelerde olumlu ve nötral değerlikli resimlere göre daha yüksek hemodinamik etkinliğe sebep oldu (pFDR<0.05). Her uyarı durumu, İYKAS ile tanımlanabilen, belirgin ve ayrışabilir bir kortikal hemodinamik etkinlik örüntüsüne sebep oldu.
Sonuç: Bulgularımız, farklı temel duyguların prefrontal korteks bölgesinde taşınabilir bir İYKAS sistemi ile ölçülebilen, ayrışabilir ve farklı yerleşime sahip hemodinamik karşılıkları oldukları görüşünü desteklemektedir. Farklı duygusal durumlar ile ilişkili farklı kortikal hemodinamik etkinlik örüntülerinin bulunması, İYKAS teknolojisinin gelecek sağlık ve gündelik hayat uygulamalarında, duyguları nesnel ve gerçek zamanlı çözümleme potansiyelini göstermektedir.

Anahtar Kelimeler: İşlevsel yakın kızılaltı spektroskopi, beyin bilgisayar arayüzü, prefrontal korteks, duygusal değerlik

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INTRODUCTION

Identification of the neuronal basis of how basic emotions are processed and regulated in healthy adult brain has received considerable attention in recent decades thanks to recent advances in mobile brain imaging technologies [1]. From a clinical perspective, precise quantification of the neural correlates of negative and positive emotions in normal, healthy subjects can enable construction of a baseline neurophysiological model, which in turn, can be used for differential mapping of the neuronal underpinnings of the same emotions in psychiatric conditions [2,3]. Besides the potential for assisting clinical diagnosis and follow-up procedures in clinical psychiatry, unravelling the spatiotemporal patterns of the neuronal circuitries involved in emotion processing and regulation can form a basis for designing affective brain computer interfaces (BCI) which aim at real-time decoding of cognitive and affective neural responses to environmental stimuli in daily settings. Such affective BCI designs can be helpful for objective detection of intent, feelings, preferences and emotional responses of patients who cannot verbally communicate with the external environment (e.g., patients with dementia, minimally conscious state and/or locked-in syndrome) [1-3].

The potential of affective BCIs for the above mentioned applications necessitates accurate detection of neuronal processing of emotional stimuli with wearable, ergonomic and miniaturized sensors which should ideally measure and decode neuronally induced signals in real-time and non-invasively, in naturalistic settings [4,5]. To this end, various functional brain imaging modalities have been utilized for characterizing the neuronal processing of emotional stimuli. These modalities include stationary systems such as positron emission tomography (PET), functional magnetic resonance imaging (fMRI) as well as portable systems such as electroencephalography (EEG) and functional near infrared spectroscopy (fNIRS). Among these modalities, fNIRS systems have been found to be ideal candidates for real-time mapping of the neural substrates of basic emotions, thanks to their robustness to electrogenic or motion artifacts, portability, quick set-up time and calibration, low-cost, ease of use and ability to collect biological information in naturalistic daily settings, at any desired frequency and duration [1-5].

fNIRS is a novel, wearable and non-invasive optical brain imaging technology which can measure localized changes in the concentration of oxygenated (HBO) and deoxygenated hemoglobin (HBR), induced by alterations in the metabolic activity of cortical neurons [6]. The operating principle of these systems rely on transmitting two different wavelengths of near infrared light which correspond to the absorption peaks of HBO and HBR molecules in the near infrared portion of the electromagnetic spectrum [7]. Unlike EEG systems, fNIRS systems are not susceptible to electrogenic or motion artifacts and they have quicker set-up time and calibration while providing higher spatial resolution. Although fNIRS systems provide poorer spatial resolution when compared to PET and fMRI, they have the major advantage of having miniaturized, ergonomic probe designs, field deployability, non-invasiveness, ability to collect data at any desired frequency and duration, as well as low operating costs. Similar to fMRI, fNIRS systems measure localized changes in cerebral hemodynamics, but unlike fMRI, these systems do not have loud operating sounds, while they provide higher temporal resolution for sampling local hemodynamic signals. Another major advantage of fNIRS over EEG, fMRI and PET systems relies on the capability of these systems to collect cerebral hemodynamic data in ecologically valid postures and environments during a variety of tasks that require mobility (e.g., walking, biking, driving). Computational cost of fNIRS signal processing is also less intensive than fMRI and EEG systems [6,7]. Overall, these features make fNIRS an ideal candidate for studying the neural basis of emotions as well as developing affective BCIs which can decode feelings, intents and/or preferences of subjects, from measurements of neuronally induced bio-signals.

Previous functional neuroimaging studies have presented compelling evidence that the human brain encompasses cortical and subcortical neuronal circuitries, that interact with each other for processing emotional stimuli. These studies have demonstrated that subregions of

anterior portion of the prefrontal cortex (PFC) have significant roles in processing, appraisal, integration and regulation of emotion related information [8,9]. The ability of fNIRS technology to easily collect functional information from the PFC region makes it an ideal tool to be integrated into affective BCI systems. However, the first step towards integrating fNIRS technology into an affective BCI system is to identify whether processing of different basic emotions have distinct and separable spatiotemporal patterns in the anterior PFC that is detectable by fNIRS. Previous fNIRS studies reported mixed results on the cortical localization and the extent of hemodynamic activation during processing of negative and positive valence stimuli [10-12]. The discrepancies in the reported spatiotemporal patterns of hemodynamic signals might have stemmed from differences in experimental design, stimuli type, possible interferences from other cognitive tasks performed involuntarily or as part of the experimental protocols. Nonetheless, the temporal and spatial characteristics of the fNIRS signals associated with processing of different emotions still remains uncertain.

The present study aimed to evaluate the feasibility of a mobile and wearable fNIRS system for objective identification of the PFC regions involved in the processing of basic emotions. More specifically, we aimed to compare the spatial localization of cerebral activation during presentation of neutral, negative and positive valence pictures in the absence of any interfering stimuli. Our research question focused on whether different basic emotions had distinct and separable hemodynamic correlates in the PFC region that could be measured and identified with fNIRS. In order to answer this question, an experimental protocol was designed in which healthy subjects passively viewed pictures that were rated as pleasant, neutral and unpleasant in the International Affective Picture System (IAPS) database [13], while interference from any other cognitive and/or physical stimuli was minimized. Pictures were chosen from the IAPS database because it provides standardized, high quality and realistic pictures with predefined valence and arousal scores. Within the context of identifying emotions with behavioral data, dimensional models describe each emotion with a two dimensional space [14], which spans valence (i.e., the extent of negative or positive feeling) and arousal (i.e., intensity of perceived feeling). Pleasant and unpleasant pictures with similar valence and arousal scores were selected in order to i) test whether the hemodynamic activity of the PFC regions during processing of basic emotions could be spatiotemporally mapped with fNIRS methodology, and ii) to obtain similarities and differences of the PFC circuitries which were activated during processing of negative, neutral and positive valence stimuli.

METHODS

Subjects

Thirteen right-handed, healthy subjects, with ages ranging from 18 to 25 years (mean age: 21 ± 2 years, 8 females, 5 males) participated in the study. Subject inclusion criteria required the absence of prior history of neurological or psychiatric disorders and being medication-free. All subjects signed informed consents prior to the experiment. The experimental protocol was conducted in accordance with the latest revision of the Declaration of Helsinki. The study was approved by the local ethics committee of Istanbul Medipol University, Istanbul, Turkey.

Experimental Protocol

During the experiment, subjects were seated on a comfortable chair in front of a computer screen which was placed approximately one meter away from their eyes. The experimental protocol was briefly explained to each subject prior to the onset of each experiment. Subjects were instructed to passively look at the images presented on the computer screen, and they were requested to sit relaxed and avoid any movement. The room was dimly lit and quiet.

The experimental protocol was adopted from a pioneer study conducted by Hermann et al. [10]. Briefly, each experiment began with a sixty second baseline recording which was followed by three stimulus blocks of ninety second duration separated with 120 second interstimulus intervals. Within each stimulus block, fifteen pictures with similar valence and arousal scores were presented consecutively for six seconds. The pictures were selected from the IAPS database

[13] and each stimulus block contained pictures of similar valence and arousal scores. Negative pictures had an average pleasure rating of 2.5 and arousal rating of 5.6. Neutral pictures had an average pleasure rating of 4.9 and arousal rating of 2.6. Positive pictures had an average pleasure rating of 8 and arousal rating of 4.8 according to the IAPS norms. The first stimulus block consisted of negative valence stimuli and the last stimulus block consisted of positive stimuli. Neutral stimuli were always presented as the second block. Subjects were requested to passively look at a white crosshair which appeared at the center of a black screen during the 120 second interstimulus rest intervals. Timing of the experimental stimuli blocks is depicted in Figure 1A.

fNIRS Data Acquisition

Hemodynamic signals were collected from the PFC region with a mobile fNIRS instrument (NIRSport, NIRx Medical Technologies, LLC, Berlin, Germany). Light source-detector pairs with a distance of 3 cm were accepted as channels. A total of twenty channels covered the forehead region (Figure 1B). Each light source emitted near-infrared light at 760 nm and 850 nm in continuous wave mode with a sampling frequency of 7.81 Hz. Light intensity changes detected at each detector were transformed to relative concentration changes of HBO and HBR with respect to a baseline reference measurement by use of the modified Beer–Lambert Law [6,7]. The MNI space coregistration of channel locations was performed with the NIRS_SPM toolbox [15]. fNIRS probe configuration and channel locations are presented in Figure 1B-C.

Pre-processing of fNIRS signals and hemodynamic parameter extraction

fNIRS signal pre-processing was carried out with a combination of scripts written in MATLAB software (Mathworks, Natick, MA, USA) and functions from the Homer2 software [16]. For each channel, raw light intensity signals of each wavelength of light were first checked for signal quality. Light intensity signals of channels with good signal quality were first transformed to optical density (OD) change. Motion artifacts in each channel's raw time series were detected with the hmrMotionArtifact.m function in the MATLAB compatible toolbox of Homer2 software. Time segments with motion artifacts were corrected with a Spline interpolation method. Motion corrected OD signals of each wavelength were then band-pass filtered between 0.005Hz and 0.08Hz with a 4th order Butterworh filter. Filtered OD data were transformed to concentration changes of HBO and HBR via Modified Beer-Lambert Law. Only HBO signals were utilized for further analysis because changes in HBO concentration have been reported to be a better indicator of cortical hemodynamic activation induced by changes in neuronal metabolism when compared to HBR signals while having a higher signal to noise ratio [6,7].

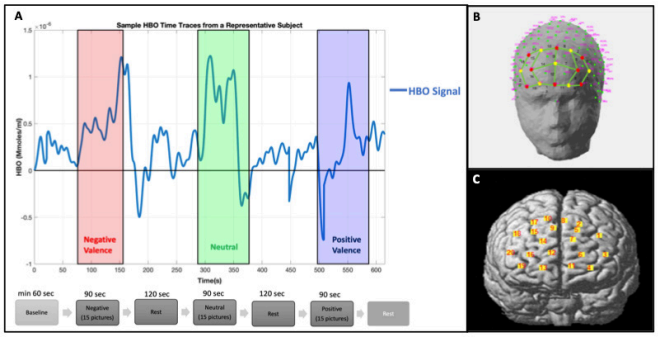

Figure 1. A) Experimental protocol and stimulus timing. A sample time trace of HBO concentration change is plotted on top of stimulus epochs for a representative channel from a representative subject. Stimulus epochs are shaded in red, green and blue for negative, neutral and positive valence stimuli respectively. B) fNIRS forehead probe configuration. Location of light sources and detectors are given according to the international EEG 10-20 system for electrode placement. Red dots represent light sources and yellow dots represent detectors. Source-detector pairs with a distance of 3 cm are accepted as channels which are represented with green lines. C) Location of channels in MNI space.

For each channel HBO time series signal, each stimulus block was truncated with a 10 second prestimulus baseline and a 20 second post-stimulus duration, resulting in 120 second long block segments for negative, neutral and positive valence stimuli periods. Linear trend in each block segment was removed with the 'detrend' function of MATLAB toolbox which performs linear fitting and removal. For each subject data, time points in each block segment were normalized with respect to the extent they deviate from the mean of the signal by a z-score transformation. Area under the curve (AUC) between 20 to 40 seconds after stimulus onset was then computed as the hemodynamic activity parameter for each channel and stimulus block segment.

Statistical Analysis

Localization of significant hemodynamic responses to each stimulus condition was determined by performing one sample student's t-test on the channel-wise AUC parameters of the subject group. For each stimulus condition, channels with t values surpassing the statistical threshold ($p<0.05$) were accepted as significantly activated in response to the presented stimuli. T values of significantly activated channels were coregistered onto a standard brain template which also depicted anatomical locations of the optode positions with respect to the 10-20 EEG system for electrode placement (Figure 2). To evaluate contrasts among different stimulus conditions, one-way repeated measures ANOVA was performed for each channel's group-wise AUC data separately with condition taken as the main effect. For each channel-wise ANOVA test, Greenhouse-Geisser correction was applied to the degrees of freedom when necessary. Post-hoc t-tests were performed with Bonferroni correction for pair-wise comparisons of three contrasts: Negative>Neutral, Negative>Positive and Positive>Neutral. All statistical analyses were conducted with MATLAB software. To localize anatomical regions depicting significant contrasts, t values of channels surpassing the Bonferroni correction were projected onto a standard brain template illustrating the anatomical locations with 10-20 EEG system (Figure 3).

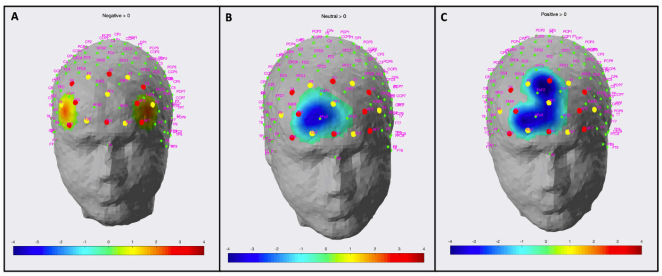

Figure 2. Statistical parameter maps of significant hemodynamic activation during A) negative, B) neutral and c) positive valence stimuli. Thresholded t-statistics of channels with significant activation are projected onto a standard head model for each condition. The color bars represent t values.

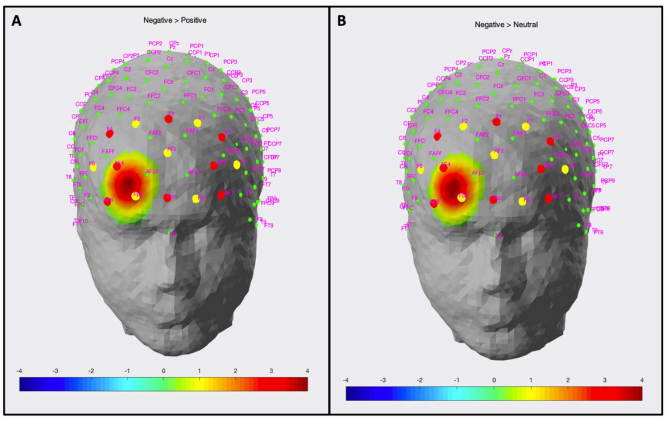

Figure 3. Statistical parameter maps depicting significant hemodynamic activity difference for A) Negative>Neutral, B) Negative>Positive contrasts. Thresholded t-statistics of channels with significant activation are projected onto a standard head model for each condition. The color bars represent t values.

RESULTS

Figure 2 demonstrates localization of statistically significant PFC activation during processing of a) negative, b) neutral and c) positive valence stimuli. Two channels (Channels 3 and 20), located bilaterally at the dorsolateral prefrontal cortex regions (DLPFC), demonstrated significant activation during presentation of negative stimuli ($p<0.05$). Three channels in frontopolar regions (Channels 12,14,16; Brodmann Area 10) demonstrated a significant hemodynamic deactivation with respect to the baseline during presentation of neutral stimuli ($p<0.05$). Four channels located in medial prefrontal cortex (MPFC) and DLPFC regions (Channels 9,10,12,16; Brodmann Area 9 and 10) showed hemodynamic deactivation during presentation of positive stimuli ($p<0.05$).

Results from channel specific one way repeated measures ANOVA analyses demonstrated statistically significant activation differences among the three stimulus conditions in two channels (Channel 16 [$F(2, 36) = 3.36$, $p = 0.046$] and Channel 19 [$F(2, 36) = 5.68$, $p = 0.0072$]). These two channels are located in the right hemispheric portion of Brodmann Area 46 and 10 and they probe right DLPFC and orbitofrontal cortex (OFC) regions. Bonferroni corrected post-hoc t-tests demonstrated that AUC parameters obtained during negative valence stimuli were significantly greater than those of both neutral and positive valence stimuli in these regions. No significant

hemodynamic activity difference was detected between neutral and positive valence stimuli conditions. Activity loci of channels surpassing the Bonferroni corrected t-score threshold are mapped onto standard head models for the following pairwise comparisons: Negative>Neutral and Negative > Positive contrasts in Figure 3. Table 1 demonstrates the extent and localization of significant hemodynamic activation during different conditions and contrasts.

Table 1. Extent and localization of significant hemodynamic activation during different conditions and contrasts

Condition	Number of Active Channels	Activity Localization
Negative Stimuli	2 (Channels 2,3)	Right and Left DLPFC
Neutral Stimuli	3 (Channels 12,14,16)	Frontopolar Area
Positive Stimuli	3 (Channels 9,10,12)	MPFC and Right DLPFC
Negative> Positive	2 (Channels 16,19)	OFC and right DLPFC
Negative>Neutral	2 (Channels 16,19)	OFC and right DLPFC

DISCUSSION

In the present study, we utilized a novel and emerging functional neuroimaging modality named fNIRS to explore the differential cortical hemodynamic activation patterns in the human PFC, during processing of negative, neutral and positive valence emotional stimuli. Our research question focused on whether different basic emotions had distinct hemodynamic correlates in the PFC region that could be identified with fNIRS. We addressed the spatial localization of cortical activation in PFC during presentation of neutral, negative and positive valence pictures which would induce pleasant and unpleasant emotions with a wearable, non-invasive and portable imaging system in a real-world setting. In the subsequent sections, the neuroanatomical and neurophysiological interpretation of the differential activation patterns are discussed in detail.

In our study, negative valence emotional stimuli induced higher hemodynamic activation in the right lateralized regions involving DLPFC and OFC regions, when compared to processing of neutral and positive emotional stimuli (Figure 3). This result is in accordance with the valence hypothesis which is based on the premise that left PFC regions are activated while processing positive valence emotional stimuli, while right PFC regions are activated in response to negative valence emotional stimuli [17,18]. Our study design involved a passive emotion inducing task which did not have any interfering cognitive tasks or self-monitoring requirements. Hence, we propose the resulting activation patterns would be solely induced by the valence of the visual stimuli. DLPFC and OFC have been considered to act as relay centers for integrating emotional, memory-related and sensory information. Such an integration of cognitive and emotional processes has also been stated to have a role in controlling emotional reactions and behavioral responses. Neural activity in OFC has also been related to computation of motivational and emotional value of the presented stimuli [19,20]. Hence, differential activity observed in these regions highlights the fact that our experimental stimuli induced the desired hemodynamic contrast in expected cerebral regions and could be used to test our hypotheses.

Negative valence stimuli induced significant increase in hemodynamic activity in both right and left DLPFC regions. DLPFC has a role in regulating both attention and emotion [20]. Significant activity of DLPFC during processing of negative stimuli might indicate that attention was being reflected towards the presented stimuli. DLPFC regions also regulate emotion through reappraisal of the presented stimuli. Thus, it is possible that the bilateral DLPFC activation occurred due to the cognitive demand for regulating emotion.

MPFC regions are involved in a variety of neural processes involving representation and maintenance of attentional demands during cognitive, motor and/or action monitoring tasks [21], while they also constitute a major hub of the default mode network (DMN). The DMN is a network of brain regions which produce coherent electrical and hemodynamic signals while the individual is at rest and not performing any attention demanding tasks. The hemodynamic activity and coherence of DMN regions are suppressed when the individual is engaged in these types of tasks [22]. The deactivation observed in MPFC regions, which include a major hub region of DMN might be related to suppression of this network due to reappraisal of the presented stimuli as an internal cognitive task. Similar to our study, Hoshi et al.

observed a significant decrease in BA10 during processing of pleasant stimuli [3]. However, we should note that previous studies which aimed at mapping functional anatomy of pleasant emotions with fNIRS, fMRI and PET modalities have revealed mixed results, which may have been due to variations in experimental stimuli and protocol [23,24]. George at al. also observed significant decreases in regional cerebral blood flow in a wide range of cortical regions, including subregions of the right PFC, during processing of transient happiness states [23]. Although the physiological interpretation of decreases in hemodynamic activity was not clearly discussed in the work of George et al., Geday et al. observed a similar decrease in regional cerebral blood flow in response to processing of emotional stimuli, and linked the significant decrease in cerebral blood flow to attenuation of default mode network function [24], which might also be one possible reason for the decrease in hemodynamic activity observed in our study during processing of neutral and negative valence stimuli.

Limitations

Recent studies which focused on gender differences in brain activity during emotional induction tasks, have suggested that women have a tendency to present stronger hemodynamic activity in response to negative valence stimuli, when compared to men [24,25]. However, we were unable to evaluate gender differences due to a limited cohort size. As an extension of this study, future work will involve collecting hemodynamic data with the same experimental protocol from a broader group of subjects, and it will include experimental designs which involve a variety of specific emotion-related tasks that are controlled for valence and arousal scores of each stimuli. To obtain more precise neural activity induced hemodynamic maps of emotional states, the impact of different levels of negative and positive valence emotional stimuli on the resulting spatiotemporal patterns of PFC hemodynamic activations, will also be thoroughly investigated with the presented optical imaging technology in future work. Functional mapping of the same stimuli will be repeated in a larger cohort of subjects, in order to test whether or not the loci of functional activation in response to the three stimulus conditions were biased with any statistical thresholding issues.

CONCLUSION

The presented study aimed to identify the PFC regions involved in the processing of basic emotions through analysis of the spatiotemporal patterns of hemodynamic activity, obtained with a mobile fNIRS system. The distinct cortical hemodynamic activity patterns associated with each emotional state show the promise of fNIRS technology for decoding and differentiating basic emotions objectively and in real time, for future applications.

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Ethics Committee Approval: This research protocol was approved by the Istanbul Medipol University Non-invasive Clinical Research Ethics Committee (Approval Date: 08.10.2020, Decision Number: 765).

ORCID and Author contribution: SBE (0000-0001-6028-3477): Concept and Design, Data collection, Literature search, Analysis and Interpretation, Manuscript Writing, Critical Review.

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