fNIRS contains usable stimulus information much earlier than the canonical HRF peak

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***Abstract*— Functional near-infrared spectroscopy (fNIRS) is often considered temporally limited due to the delayed peak of the hemodynamic response. This study investigates whether meaningful, stimulus-related information can be extracted from the early post-stimulus interval (0–2.5 s) during vibrotactile stimulation. Data from 13 participants across multiple stimulation locations and frequencies were analyzed using time-locked averaging, spectral validation, and linear mixed-effects modeling. Results show that early hemodynamic responses are reproducible, stimulus-locked, and spatially specific. While mean amplitude did not significantly differentiate conditions, maximum amplitude revealed significant stimulus- and location-dependent effects, and the slope of the response captured spatial organization consistent with somatosensory mapping. Control analyses confirmed that these effects are not driven by systemic noise or stimulation artifacts. These findings demonstrate that fNIRS contains usable and physiologically meaningful information earlier than traditionally assumed, supporting its potential for rapid detection of cortical activity in real-time applications.**

Keywords—vibrotactile, functional near-infrared spectroscopy, ERP

I. INTRODUCTION

Functional near-infrared spectroscopy (fNIRS) is a non-invasive neuroimaging modality that measures changes in cortical hemoglobin concentrations associated with neural activity [1]. Due to its portability, safety, and tolerance to movement, fNIRS has become increasingly popular for studying brain function in naturalistic settings and for applications such as brain–computer interfaces (BCIs) [2], [3] However, a fundamental limitation of fNIRS is the relatively slow temporal evolution of the hemodynamic response, with the canonical hemodynamic response function (HRF) typically peaking several seconds after stimulus onset [4], [5]. As a result, fNIRS is often considered unsuitable for rapid detection of stimulus-related events.

Despite this limitation, emerging evidence suggests that the early phase of the hemodynamic response occurring within the first few seconds following stimulus onset may contain meaningful information related to neural activity [6]. However, the reliability, spatial specificity, and physiological origin of these early signals remain insufficiently understood, unlike other modalities like EEG, MEG and functional processes [7]–[9] . In particular, it is unclear whether early fNIRS responses reflect genuine cortical activation or are confounded by systemic physiological fluctuations (e.g., cardiac, respiratory, and Mayer wave activity) or by stimulation-induced artifacts, especially in paradigms involving vibrotactile stimulation.

Addressing these uncertainties is critical for determining whether early hemodynamic signals can be used for rapid detection and real-time applications. If early responses are reproducible, spatially localized, and robust to potential noise sources, they could enable faster interpretation of cortical activity than is typically assumed for hemodynamic imaging. In this study, we investigate whether fNIRS signals contain consistent, stimulus-locked information within the early post-stimulus interval (0–2.5 s) during vibrotactile stimulation (VBT) applied across multiple anatomical locations and stimulus conditions.

We applied VBT to observe the fNIRS responses in the somatosensory cortex across two different frequency components and four different stimulation locations. VBT is classically known to evoke a clear electrophysiological [10]–[12] and haemodynamic [13] change in the SCx. Therefore, it serves as an optimum stimulus to assess the suitability of yielding ERP-like fNIRS signals. We expect to see time-locked, repetitive evoked responses.

We first examine whether early hemodynamic responses are reliably evoked and temporally aligned with stimulus onset across trials. To address potential confounds, we evaluate the influence of both stimulation-induced artifacts and systemic physiological noise using spatial, temporal, and spectral analyses. Finally, we characterize early hemodynamic dynamics using summary metrics, including mean amplitude, maximum amplitude within the early window, and the slope of the response, to determine whether meaningful information is present prior to the canonical HRF peak.

Together, these analyses aim to establish whether the early phase of the fNIRS signal contains usable and physiologically meaningful information, thereby supporting its potential for rapid detection of sensory events.

II. METHODS

A. Experimental Paradigm

Data was collected from 13 right-handed. Ethical approvals were obtained from the institute's ethical committee.

Stimuli were employed across four locations: the index finger, arm, leg and toe. Two stimulation types were delivered across these locations, henceforth referred to as Stim 1 and Stim 2. Stim 1 and 2 differed in vibration frequency (300 Hz and 60 Hz, respectively). Each stimulus was presented for a duration of 1 s, followed by an interstimulus interval (ISI) of 1.5 s. The combination of four stimulation locations and two

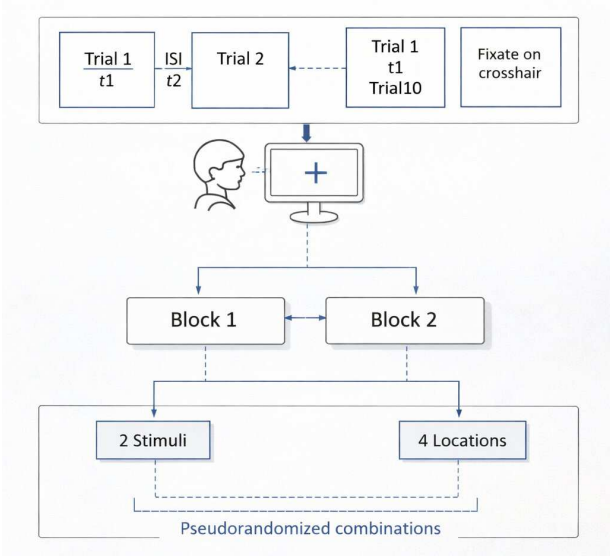

Fig. 1 The schematic diagram of the experimental paradigm is shown. Two types of stimulation frequencies were applied across four locations in a pseudorandomized manner across subjects. Under each condition, 200 stimuli are deployed in two blocks (100 stimuli each) followed by a rest period of 15 seconds.

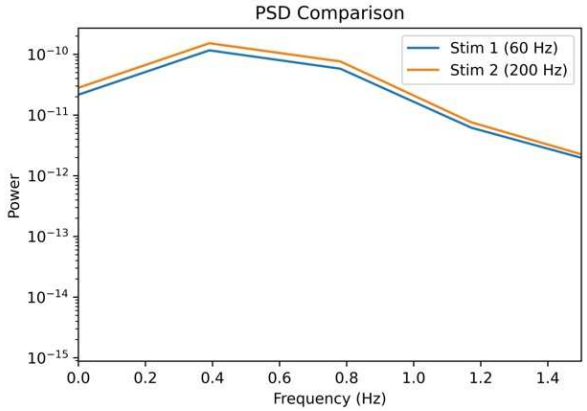

Fig. 2 Power spectral density (PSD) of fNIRS signals for the two stimulation conditions (60 Hz and 200 Hz), computed using Welch's method. The spectral profiles show similar distributions across frequencies, indicating no prominent frequency-specific artifacts.

frequency conditions yielded a total of eight experimental conditions.

Each condition consisted of 200 trials, organized into two blocks of 100 trials each. The order of presentation was controlled to ensure balanced exposure across conditions.

B. Stimulus delivery and data acquisition

The g.Nautilus fNIRS module (g.tec medical engineering GmbH) was integrated with the g.GAMMAcap and positioned on the participant's head. The system comprised two detector optodes, each surrounded by four sources, yielding a total of eight measurement channels. Dual wavelengths (760 nm and 850 nm) were used to estimate changes in oxyhemoglobin (HbO) and deoxyhemoglobin (HbR) concentrations. The detectors were placed at C3 and C4 according to the international 10–20 system, ensuring coverage of regions anterior and posterior to the central sulcus within each hemisphere, corresponding to the sensorimotor cortex. The differential pathlength factor (DPF) was set to 4.

The data was acquired at a sampling frequency of 500 Hz and later resampled to 100 Hz for efficient data processing. Vibrotactile stimulation was delivered using C2 and C2-HDLF tactors (Engineering Acoustics, Inc.). The stimulation settings on the tactors were controlled via dedicated APIs using a Visual C++ script, enabling precise control over the amplitude, frequency, and duration of stimulation.

C. Data Processing

The hemoglobin concentration signals and the corresponding trigger channel were extracted and resampled to a uniform sampling rate of 100 Hz. The resulting data were stored as continuous MNE Raw objects for further processing.

The data were then band-pass filtered between 0.02 and 0.7 Hz using a finite impulse response filter to attenuate slow baseline drift and high-frequency physiological noise such as cardiac pulsations. Following filtering, each dataset was visually inspected, and segments or channels affected by excessive noise or motion artifacts were identified and excluded through manual inspection. Cleaned data were saved for subsequent analysis.

For each condition, trial-wise epochs were averaged to obtain evoked responses for HbO signals. Baseline correction between -200ms to -50ms from the onset of the stimulus was applied. Evoked responses were computed at both the individual subject level and aggregated across subjects using grand averaging to obtain condition-specific group-level responses. Following this, a series of validation checks were performed to ensure that the observed signals were not contaminated by potential artifacts, as detailed in the subsequent subsections.

D. Power spectral densities

The first sanity check involved evaluating potential contamination from vibrotactile stimulation. Epoch-level signals were grouped by stimulus condition and concatenated across subjects. Power spectral density (PSD) analysis was performed using Welch's method (see Fig. 2) to examine the distribution of signal power across frequencies. The spectral profiles were compared between stimulation frequencies (60 Hz and 200 Hz) to assess the presence of frequency-specific artifacts or aliasing effects.

E. Visualization of early ERP-like response

The second sanity check was conducted to evaluate the feasibility of an ERP-like paradigm for fNIRS by testing for the presence of time-locked event-related responses (see Fig. 3). To implement the sanity check, the raw data at the subject level were segmented into epochs, with time points ranging from 200ms prior to the stimulus to four times the time duration of each stimulation trial (consisting of the stimulation duration and the interstimulus interval). Therefore, specific to the sanity checks, each epoch would contain 4 stimulation trials. These epochs were averaged to produce the subject-level evoked response. Subsequently, the

data were averaged across the same conditions to generate the grand average response, which was then plotted.

F. *Visualization of spatial distribution of early ERP-like response*

Further sanity check was conducted to check for distinct spatial patterns across ipsilateral and contralateralal signals (see Fig. 4). The ipsilateral and contralateral channels were selected. For each hemisphere, responses were averaged across channels to obtain hemisphere-wise time courses. These hemisphere-averaged signals were subsequently visualized to facilitate qualitative comparison of temporal dynamics between the two hemispheres.

G. *Summary metrices*

To specifically investigate early hemodynamis, summary metrics were extracted from the evoked HbO and HbR responses within the 0–2.5 s post-stimulus interval. The following features were computed for each channel:

- Mean amplitude: average signal within the early window
- Maximum amplitude: peak value within the early window
- Slope: linear rate of change of the signal over time

These features were computed for each subject, location, stimulus condition and compiled into a structured dataset for statistical analysis.

H. *Statistical Analysis*

A linear mixed-effects modeling approach [14] was used to evaluate the effects of stimulus and location on the extracted features. Fixed effects included stimulus condition and stimulation location, while subject-level variability was modeled as a random effect. Separate models were fitted for each feature (mean, maximum amplitude, and slope), and model comparisons were performed using likelihood ratio tests. For statistical significance, a p-value threshold of 0.05 was used.

TABLE I. EFFECT OF STIMULATION CONDITIONS (STIMULUS, LOCATION AND THEIR INTERACTION) ON EARLY fNIRS RESPONSES

Metric	**Stimulus (χ^2, p)**	**Location (χ^2, p)**	**Interaction (χ^2, p)**
Mean amplitude	2.83, 0.093	6.01, 0.305	8.11, 0.150
Max amplitude	35.07, <0.001***	25.92, <0.001***	29.86, <0.001***
Slope	2.26, 0.133	13.61, 0.018*	1.96, 0.854

III. RESULTS

A series of validation checks were first performed to ensure that the observed signals were not driven by potential artifacts. Following this, the data were analyzed to assess whether early hemodynamic responses could reliably encode stimulus- and location-specific information. The same is explained below.

A. *Power spectral densities*

The PSD profiles for both stimulation conditions (60 Hz and 200 Hz) showed similar distributions (see Fig. 2), with dominant power in the low-frequency range (≈0.3–0.5 Hz) and no distinct peaks at the stimulation frequencies. The overlap between conditions indicates that the spectral characteristics are not influenced by the stimulation frequency. This suggests that the observed signals reflect intrinsic hemodynamic activity rather than vibration-induced artifacts.

B. *Stimulus-locked early ERP-like response*

The presence of consistent response patterns across multiple stimulation cycles (see Fig. 3) indicates that the hemodynamic signals are reproducible and time-locked to the stimulus. This repeated structure demonstrates that the measured fNIRS signals reliably track sensory stimulation

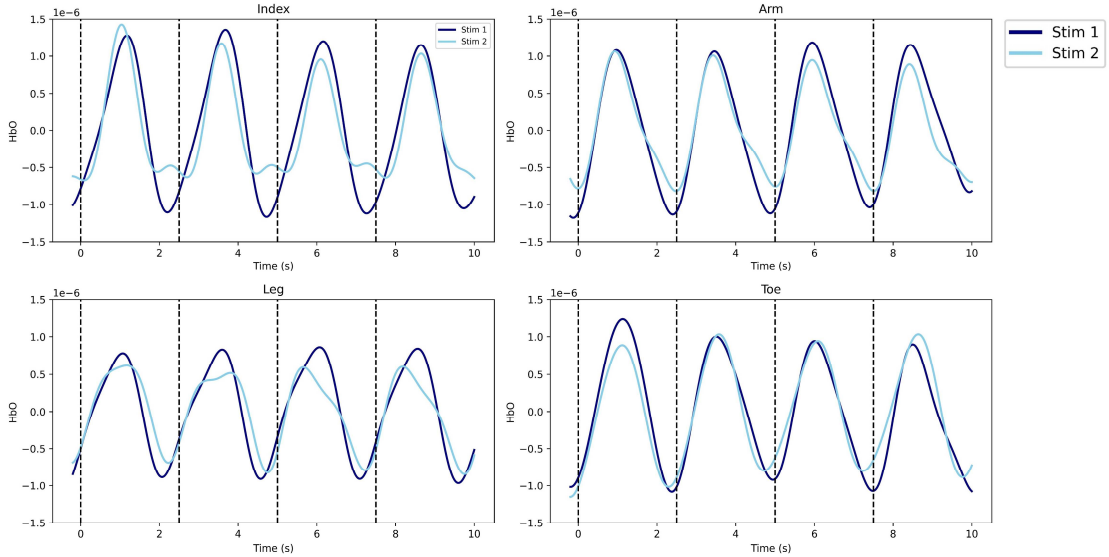

Fig. 3 Grand-averaged HbO responses across four stimulation sites for two vibrotactile conditions. The repeated, stimulus-locked structure across cycles (dashed lines indicating stimulus onset) highlights the presence of consistent early hemodynamic dynamics preceding the canonical peak.

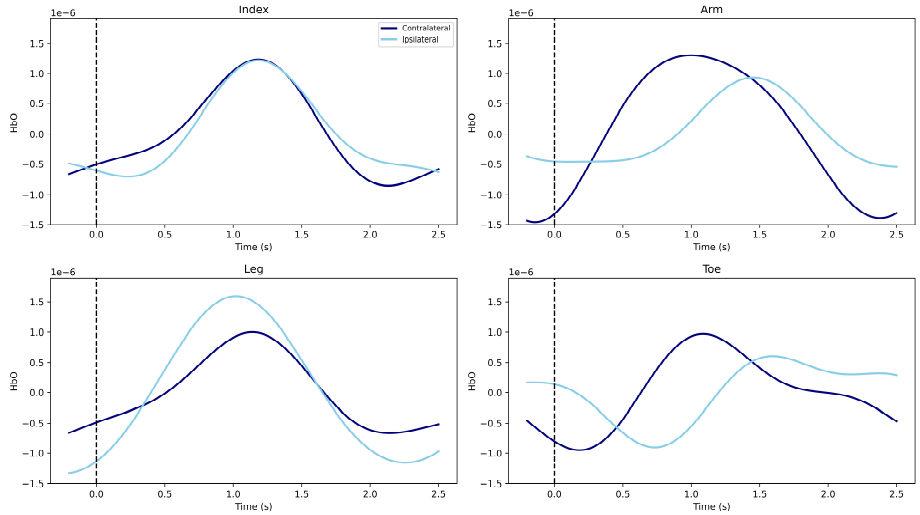

Fig. 4 Early (0–2.5 s) HbO responses across four stimulation locations (index, arm, leg, and toe) for ipsilateral and contralateral hemispheres. The dashed vertical line indicates stimulus onset. Distinct temporal and amplitude differences between hemispheres demonstrate spatial specificity, suggesting that the observed responses are not driven by global or systemic effects but reflect localized cortical activation.

events rather than reflecting random fluctuations or transient noise. Such early dynamics may therefore be leveraged for rapid detection of sensory events, indicating that fNIRS-based measurements could support faster monitoring of cortical activity than traditionally assumed for hemodynamic imaging.

These findings suggest that, although the full hemodynamic response evolves over several seconds, its early onset contains sufficient information for detecting stimulus-related cortical activity within short temporal windows in VBT stimulation.

C. *Spatial distribution of early ERP-like response*

Following stimulus onset, a clear increase in HbO concentration is observed in both hemispheres across all locations. However, differences in response amplitude and timing are evident between ipsilateral and contralateral channels (see Fig. 4). In several cases (e.g., Arm and Toe), the contralateral hemisphere exhibits a stronger or earlier peak compared to the ipsilateral side, whereas in case of the Leg the responses show a shift in peak timing or relative amplitude between hemispheres. These differences suggest the absence of global or systemic effects due to stimulation protocols and reflect localized cortical activation.

D. *Mean Amplitude*

For mean HbO amplitude, no significant effects were observed. Stimulus as a fixed effect did not significantly improve model fit ($\chi^2(1) = 2.83$, $p = 0.093$). Similarly, inclusion of location ($\chi^2(5) = 6.01$, $p = 0.305$) and the stimulus × location interaction ($\chi^2(5) = 8.11$, $p = 0.150$) did not result in significant improvements.

These results indicate that the average magnitude of the early hemodynamic response does not strongly differentiate between stimulation conditions within the first 2.5 s following stimulus onset.

E. *Maximum amplitude within the early window*

In contrast, the maximum HbO amplitude within the early window showed robust effects. Inclusion of stimulus significantly improved model fit ($\chi^2(1) = 35.07$, $p < 0.001$), indicating that maximum amplitude differed across stimulus conditions. Adding location further improved the model ($\chi^2(5) = 25.92$, $p < 0.001$), demonstrating spatial variation in response magnitude. Importantly, the stimulus × location interaction was also significant ($\chi^2(5) = 29.86$, $p < 0.001$), indicating that the effect of stimulus varied across stimulation locations.

These findings suggest that even within the early phase of the hemodynamic response, the upper envelope of the signal contains both stimulus-specific and spatially specific information.

F. *Slope of early response*

Analysis of the slope of the HbO signal revealed a significant main effect of location ($\chi^2(5) = 13.61$, $p = 0.018$), indicating that the rate of change of the early hemodynamic response varies across stimulation sites. However, no significant effect of stimulus was observed ($\chi^2(1) = 2.26$, $p = 0.133$), and the stimulus × location interaction was not significant ($\chi^2(5) = 1.96$, $p = 0.854$). This pattern suggests that early temporal dynamics of the hemodynamic response encode spatial information but are relatively insensitive to differences in stimulus condition.

IV. DISCUSSION

The present study investigated whether the early phase of the fNIRS hemodynamic response (0–2.5 s) contains meaningful and reliable information related to vibrotactile stimulation. The findings demonstrate that, although early hemodynamic signals are subtle in magnitude, they exhibit structured temporal and spatial characteristics that are consistent with stimulus-evoked cortical activity.

A key observation of this study is the dissociation between different features of the early response. Mean amplitude within the early window did not significantly differentiate between stimulation conditions, indicating that the overall magnitude of the response remains weak during the initial phase. However, both the maximum amplitude within the early window and the slope of the response revealed systematic effects. In particular, the slope showed

significant variation across stimulation locations, suggesting that the temporal dynamics of the early response encode spatially specific information even when amplitude differences are not yet fully developed. This finding supports the notion that the rising phase of the hemodynamic response reflects underlying cortical organization, consistent with the somatotopic arrangement of the somatosensory cortex.

In contrast, the maximum amplitude within the early window showed strong effects of both stimulus and location, as well as their interaction. Although this measure does not represent the canonical peak of the hemodynamic response, it captures the upper envelope of the early signal and suggests that stimulus-specific differences begin to emerge within the first few seconds following stimulation. Together, these results indicate that different aspects of the early hemodynamic response carry complementary information: temporal features (e.g., slope) primarily reflect spatial organization, whereas amplitude-related features begin to reflect both stimulus and spatial effects.

An important aspect of this study was the evaluation of potential confounds arising from vibrotactile stimulation and systemic physiological noise. Vibrotactile stimulation can introduce mechanical artifacts that may propagate to the optodes and contaminate the measured signals. However, multiple lines of evidence argue against this possibility. First, spectral analysis revealed no frequency-specific differences between stimulation conditions, indicating the absence of aliasing or stimulation-frequency-related artifacts (see Fig. 2). Secondly, responses were consistently time-locked to stimulus onset across trials (see Fig. 3). Lastly, the observed responses exhibited clear spatial heterogeneity and hemispheric asymmetry (see Fig. 4), which would not be expected from global mechanical disturbances. Similarly, systemic physiological fluctuations, such as Mayer waves and respiratory oscillations, are expected to produce globally correlated signals across channels. In contrast, the present results showed spatially localized and condition-specific patterns, suggesting that systemic noise did not drive the observed effects.

Taken together, these findings provide converging evidence that the early fNIRS signal reflects genuine cortical activity rather than noise or artifact. Importantly, the presence of spatially meaningful information within the first 2.5 s suggests that the hemodynamic response contains usable information earlier than traditionally assumed.

Nevertheless, several limitations should be considered. The analysis was restricted to a short window, and therefore does not capture the full evolution of the hemodynamic response. As a result, the relationship between early dynamics and the canonical HRF peak could not be directly assessed. Future work could further validate these findings by designing paradigms that additionally allow the evolution of canonical peaks in fNIRS and comparison of these signals with underlying electro-neural activity after appropriate spatial registration of these functional signals [15].

In conclusion, the present study demonstrates that the early phase of the fNIRS hemodynamic response contains reproducible, spatially specific, and physiologically meaningful information. These findings challenge the conventional view of fNIRS as a purely slow modality and highlight the potential of early hemodynamic dynamics for rapid detection of sensory-evoked cortical activity.

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