Received April 27, 2020, accepted May 5, 2020, date of publication May 11, 2020, date of current version May 22, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2993620

Task-Specific Stimulation Duration for fNIRS Brain-Computer Interface

M. N. AFZAL KHAN[1], M. RAHEEL BHUTTA[2], AND KEUM-SHIK HONG[1], (Fellow, IEEE)
[1]School of Mechanical Engineering, Pusan National University, Busan 46241, South Korea
[2]Department of Computer Science and Engineering, Sejong University, Seoul 05006, South Korea

Corresponding author: Keum-Shik Hong (kshong@pusan.ac.kr)

This work was supported by the National Research Foundation (NRF) of Korea through the Auspices of the Ministry of Science and ICT, Republic of Korea, under Grant NRF-2020R1G1A1012741 and Grant NRF-2017R1A2A1A17069430.

ABSTRACT In this paper, the most effective stimulation durations in the visual, somatosensory, and motor cortices are investigated. To evoke hemodynamic responses (HRs) for the purpose of brain-computer interface (BCI) with functional near-infrared spectroscopy (fNIRS), the best and the minimal durations for three tasks (visual, tapping, and poking) are presented. The examined tasks include the checkerboard, right-hand-index-finger poking, and the right-hand-index-finger tapping tasks in association with the visual, somatosensory, and motor cortices. Upon stimulations, the peak value, time to peak, and the full width at half maximum of the HRs are examined. Six different stimuli durations (i.e., 1, 3, 5, 7, 10 and 15 sec) were tested. Ten male subjects participated in the experiment. Three types of stimulations having the same duration were presented to the subjects randomly. The stimulation durations that showed the maximum peak values in the checkerboard, poking, and tapping tasks were 7, 5, and 10 sec, respectively. The peak value increased with the increase of stimulation duration. But beyond a certain period of time, the peak value did not increase anymore and sometimes it decreased when the stimulation period is too long. It is noted that 1-sec stimulation (for all three tasks) can generate a noticeable peak value. Instead, the initial dip upon poking occurred only with 1-sec poking (i.e., initial dip did not occur in all other poking periods). Conclusively, this work reveals the possibility of a BCI command generation within 1 sec.

INDEX TERMS Brain-computer interface (BCI), stimulation duration, functional near-infrared spectroscopy (fNIRS), hemodynamic response, initial dip, poking, checkerboard, tapping.

I. INTRODUCTION

Brain-computer interface (BCI) characterizes a communication medium between the brain and peripheral devices, constructed to achieve external activities with only brain signals [1]. The new era of BCI has developed various ways to detect particular neural signals in the human brain and to decipher those signals as commands that can be used to control the associated external devices. This research has been an area of focus for researchers since 2000, prompting the inventions of several prototype systems. BCI is intended for patients, but it can be used for healthy people like pilots and drivers for specific purposes. Therefore, the objective of this study is to find out the best and minimal stimulation durations that can produce the maximal and sufficient activations in the hemodynamic response (HR) for BCI. Also, there is a need to find out an appropriate stimulation duration, which can produce an initial dip (i.e, the early decrease of ΔHbO with the start of a brain task is referred to as the initial dip [2]) that can be used accordingly. In this study, we aim to suggest the most suitable stimulation durations for three brain regions (motor, sensory, and visual cortices) for fNIRS-based BCI.

Many methodologies exist in acquiring brain signals; from the direct collection of neural firing from neurons to a decoding method of motor signals using a nerve sensor. Among these, noninvasive approaches include electroencephalography (EEG) [3]–[5], functional near-infrared spectroscopy (fNIRS) [6]–[12], functional magnetic resonance imaging (fMRI) [13], and magnetoencephalography (MEG) [14], [15]. fNIRS is a newly emerging technique that utilizes near-infrared light within the 650 nm $\sim$ 1,000 nm range (i.e., in this range, the absorption by water is negligible) to gauge the varieties of regional cerebral blood flows (rCBFs) in the brain [16], [17]. The two

The associate editor coordinating the review of this manuscript and approving it for publication was Norbert Herencsar.

chromophores absorbing near-infrared lights in the blood are oxy-hemoglobin (HbO) and deoxy-hemoglobin (HbR) [18]. Upon neuronal activities, the changes of HbO and HbR (i.e., ΔHbO and ΔHbR) in the vessels and venules occur [19], which is known as the HR that mirrors the acquaintance of more oxygen to the brain [6], [20].

fNIRS has a great potential to be utilized as a neuro-imaging device, and its applications will propagate significantly in the areas of social and psychological neurodevelopment [21], discernment and perception [22], mental disorder [23], BCI areas [24]–[27] and decoding of neuronal signals using advanced techniques [28]–[30]. Also, in contrast with entrenched imaging techniques, for example, fMRI, EEG, and positron emission tomography (PET), fNIRS offers preferences (for example, versatility, minimal effort, and lower vulnerability to motion artefacts) over other modalities. Good temporal resolution is necessary in BCI systems to generate a quick command. Also, having a good spatial resolution helps a precise identification of brain sources. But, achieving both goals requires more cost. fNIRS is known to have good temporal resolution but moderate spatial resolution than fMRI. However, research is in progress to improve its spatial and temporal resolution by utilizing bundled-optode setups and decreasing the onset delay with initial dip detection for BCI applications [31]–[34]. In comparison to EEG, fNIRS signals are more brain-region-specific than EEG, and the number of commands can be increased when a hybrid approach is pursued. Moreover, fNIRS has shown better performance over EEG in ''active'' BCI than reactive BCI, which makes it more suitable in diverse BCI applications. For more subtleties regarding fNIRS, readers can refer to [35], [36].

During the past decade, fNIRS studies have utilized various types of stimulation. In those studies, diverse brain cortices have been used for the acquisition of HR signals. The studies performed on the prefrontal cortex have utilized tasks like mental arithmetic, mental counting, and puzzle solving [37]. Studies focusing on the sensory cortex have applied thermal stimulations [38], [39], electrical stimulation [40], [41], painful pressure [42], and poking [43]. Similarly, so were the finger tapping for the motor cortex and checkerboard stimulation for the visual cortex [44]–[46].

There exist fMRI studies discussing the relationship between stimulation durations and the blood-oxygen-level-dependent (BOLD) signals [47]: The studies [48]–[50] on the primary visual cortex reported that the BOLD signal is non-linear for stimuli less than 3∼4 sec, and beyond these durations, it becomes linear from the sense that the profile follows some specific relation. Similarly, the study conducted on the primary auditory cortex [51] reported a difference in the trend of BOLD signals for stimuli under 6 sec and those for over 6 sec. A recent study by Lewis *et al.* [52] has addressed the dependence of HR timing in the subcortical-cortical regions of the visual pathway in humans. This study reported that by varying the stimulation duration, the HR response varies in both subcortical and cortical areas. Also, it was found that the HR is somewhat faster and is narrower in the subcortical areas as compared to the cortical areas. These responses were investigated for stimuli of short time (0.17∼4 sec). The authors concluded that the subcortical and cortical areas of human brain exhibit very distinct HR temporal characteristics.

In the field of fNIRS, a variety of studies have tried to vary the stimulus types and check their effects on the HR signals. One of the latest studies has discussed the effects of modulating noise stimuli on the HR [53], in which noises were modulated in four different intensity levels. The study revealed that the fNIRS response is highly dependent on the sound intensity, that is, the higher the sound intensity is, the higher the concentration change follows. Another study [54] reported the effect of checkerboard sizes and the variability due to cap positions in the HRs: The authors checked the effect of changing the visual angles of checker squares in the checkerboard task, in which 1, 2, 5, 9, and 18 degree-checker-squares were used. The results claimed that 1-degree stimulus showed the greatest activation. For the same region of brain, another study [46] evaluated the effects of reversing checkerboard, on/off checkerboard, and static checkerboard. In their study, a pattern reversal stimulation showed the greatest activation among three tasks. Also, on the prefrontal cortex, a study [55] was conducted to check the effect of a varying anagram task. In [56], the occipital and temporal responses to the repetition of stimuli in infants have also been studied. However, no fNIRS result has been reported on the effects of stimulation duration to the HR signals in different brain cortices. Also, even though diverse stimulation durations have been used in the past, but yet no standardized stimulation duration has been proposed, which demonstrates comparative results among various stimulation durations.

In this study, we take indicative steps towards standardizing the stimulation durations for individual cortices for the purpose of acquiring fNIRS data to be used for BCI. Depending on the neuro-characteristics in different cortices, different stimulation intervals are suggested. Three different tasks are performed by subjects and for all these tasks different temporal characteristics (i.e., full wave at half maximum, peak value, and time to peak) are analyzed. Simultaneous acquisitions of fNIRS data from the three brain regions are done, while random stimuli are presented to the subject. Finally, on the basis of these results, we compare the responses from different brain areas by varying stimulation durations and suggest the most favorable stimulation sizes that can well serve for the purpose.

II. METHODS

A. PARTICIPANTS

Ten male subjects (mean age: 27.2 ± 4.5 years) participated in this study. The needed number of subjects was calculated statistically using the online power calculator at http://biomath.info/power/prt.htm [57], after setting the values of the statistical level of significance (α) and the statistical power ($1-\beta$) to 5% and 80%, respectively. All subjects were

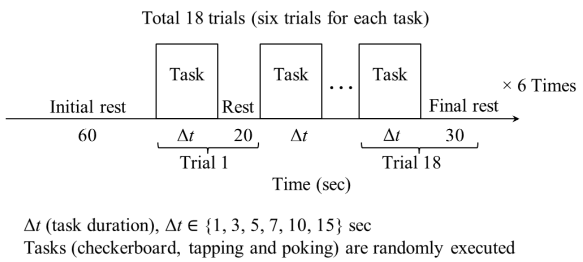

FIGURE 1. Experimental paradigm.

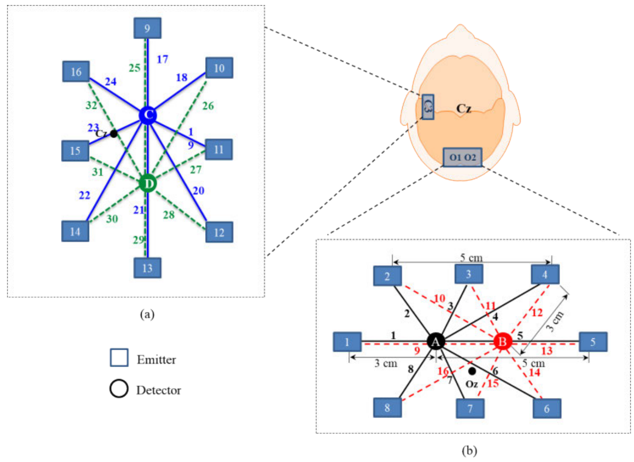

FIGURE 2. Emitter-detector configuration: (a) Sensorimotor cortex, (b) visual cortex.

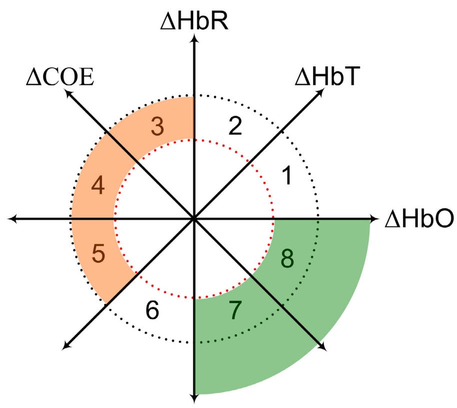

FIGURE 3. Vector phase diagram using dual threshold circles depicting the HR region (green) and the initial dip region (orange) [60].

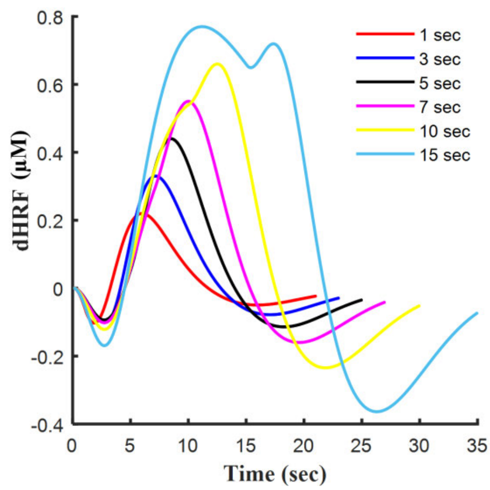

FIGURE 4. The hemodynamic responses anticipated from six different stimulation durations: Computed using three gamma functions [60].

healthy, right handed, and had normal or corrected-to-normal sight. No history of neurological or visual impairment was reported from all participants. Prior to the experiment, everyone was given a complete description of the experimental procedure and written consent was obtained from all the participants. The study was conducted in compliance with the recent proclamation of Helsinki [58] after the permission by the Institutional Review Board of Pusan National University.

B. STIMULUS DESIGN

Three different tasks were performed in experiments: They are the right-hand index finger tapping (just tapping), right-hand index finger poking (just poking), and checkerboard tasks. To check the influence of the lengths of stimuli on the HRs, six different stimulation durations (1, 3, 5, 7, 10, and 15 sec) were tested. During the experiment, the subjects were advised to perform the task appearing on the screen.

In the checkerboard task, the subjects were instructed to focus on the 19-inch screen placed one meter away from the subject. In the tapping task, the subjects were instructed to tap their finger as fast as they could, and in the poking task, the subjects were poked on the backside of the right-hand index finger at random positions with a frequency of 2 Hz. These tasks were easy to be performed by the healthy individuals, which is the reason for selecting them as tasks in the study.

C. EXPERIMENTAL PARADIGM

The tasks during the experiment were assigned randomly, i.e., the subjects were unaware of what task would appear next. Six trials for each task were conducted, making a total of eighteen random trials. For all three tasks, the left motor, the left sensory, and the entire visual cortices were examined. The participants sat on a comfortable chair and were told not to make any body/head movement as much as possible throughout the experiment not to include motion artifacts. The experiments were carried out in a dark room and the room was kept as quiet as possible to reduce the effect of external noises. The experimental paradigm depicting the inter-stimulus interval and the pre- and post-rest periods is shown in Fig. 1. The inter-stimulation interval was kept twenty seconds for all stimulation durations whereas the pre- and post-rest periods were set to 60 sec and 30 sec, respectively.

A black screen was displayed during the period of rest. Visual displays were given for all three tasks on the computer screen placed in front of the subjects. Throughout the experiment, the subjects were advised to keep their eyes open.

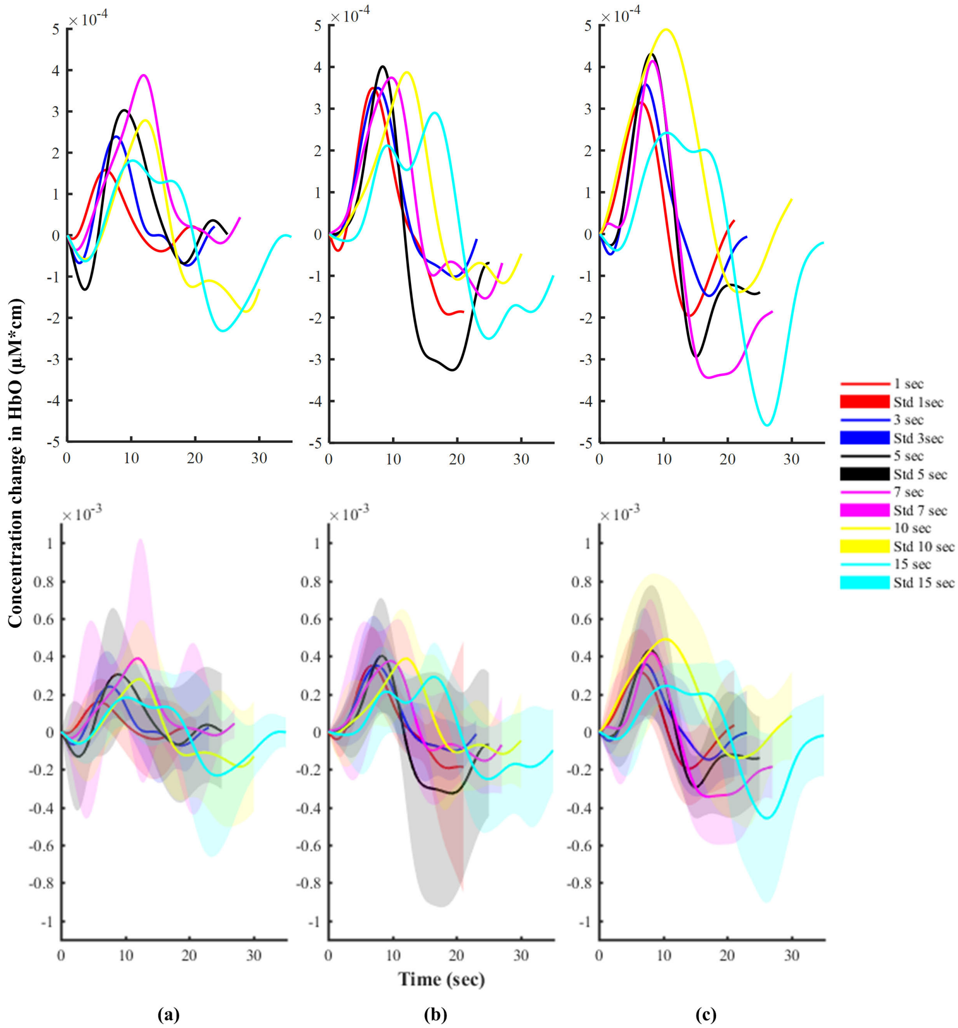

FIGURE 5. Comparison of the averaged HbOs over the activated channels and 10 subjects (top: the averaged values, bottom: standard deviations): (a) Checkerboard, (b) poking, and (c) tapping.

D. OPTODE CONFIGURATION

In this study, four detectors and sixteen emitters were positioned over the target brain regions. The emitter-detector configurations for two brain regions (sensorimotor and visual cortices) are shown in Fig. 2. In this figure, black, red, blue, and green colors are used to denote detectors A, B, C, and D, respectively. The colored lines and channel numbers are in association with the colored detectors. The numbers in the square boxes indicate the emitter numbers.

For the left sensorimotor cortex, the optodes were configured near the C3 location of the brain, whereas for the visual cortex the optodes were placed to examine O1 and O2 areas. These reference points are from the International 10-20 System for electrode placement.

E. DATA ACQUISITION

The signals from the brain were sampled at a sampling frequency of 15.625 Hz for all three tasks (tapping, poking, and checkerboard) from the left sensorimotor cortex and the primary visual cortex simultaneously. A frequency domain fNIRS system (ISS Imagent, ISS Inc.) was used for the acquisition of fNIRS data.

Raw intensity data were obtained using the ISS Imagent data acquisition and analysis software (ISS-Boxy). Two different wavelengths (690 nm and 830 nm) were utilized by the system to measure the concentration changes of oxy-hemoglobin and deoxy-hemoglobin. The modified Beer-Lambert law was used to convert the raw intensity data into ΔHbO and ΔHbR [59]. For 690 nm, the extinction coefficients were 0.95 $mM^{-1}cm^{-1}$ and 4.93 $mM^{-1}cm^{-1}$ for Δ HbO and ΔHbR, respectively, and for 830 nm the values were 2.135 $mM^{-1}cm^{-1}$ and 1.791 $mM^{-1}cm^{-1}$, respectively [60].

F. PREPROCESSING

After the acquisition of data (ΔHbO& ΔHbR), they were pre-processed to eliminate the contamination of physiological noises. A 4th-order Butterworth filter was applied with

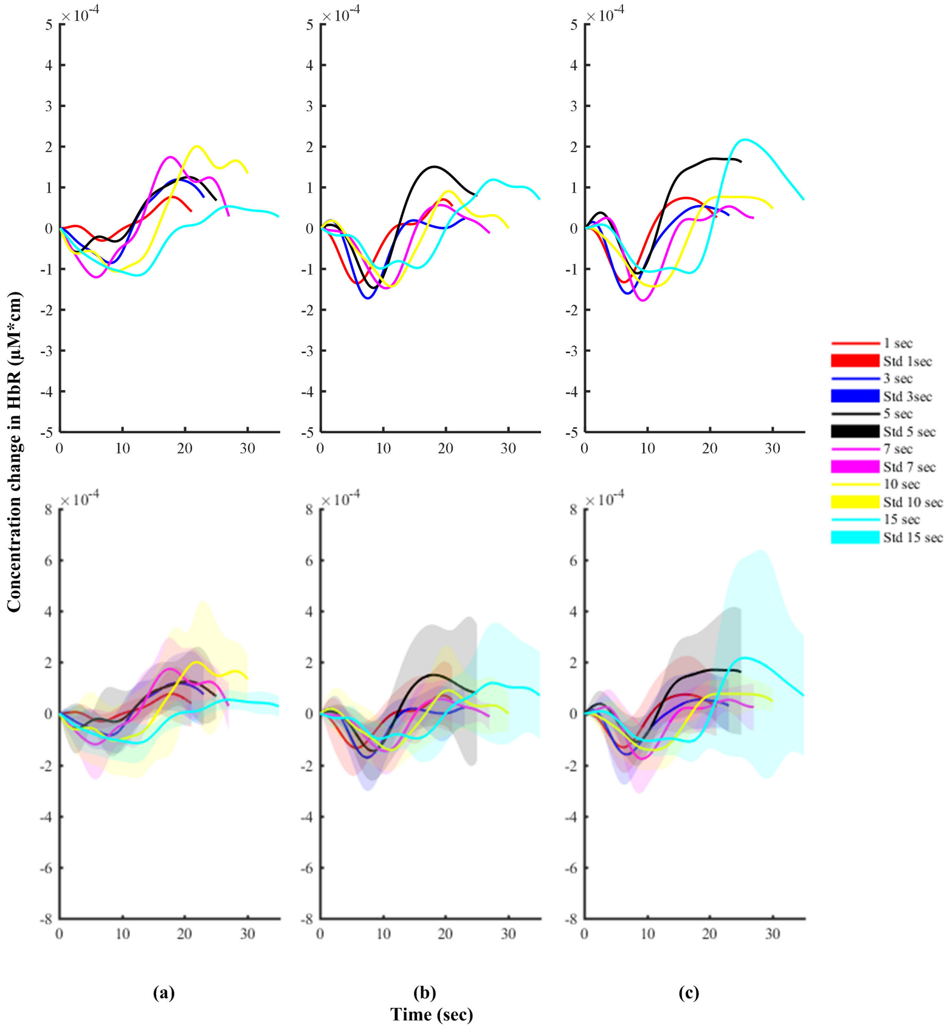

FIGURE 6. Comparison of the averaged HbRs over the activated channels and 10 subjects (top: the averaged values, bottom: standard deviations): (a) Checkerboard, (b) poking, and (c) tapping.

a low-pass cutoff frequency at 0.15 Hz to remove cardiac, respiratory and low-frequency drift signals [61]–[63]. The frequency of a high-pass filter was selected according to the longest possible time period of a trial. For each of the six different stimuli duration, the cutoff frequency was different because of the difference in the time period of a trial. For 15 sec task, the trial period was 35 sec, so the cutoff frequency was set to 0.028 Hz (1/35 sec = 0.028 Hz). Similarly, the cut-off frequencies were set to 0.047 (i.e., 1/21, where the trial period is 21 sec), 0.043, 0.04, 0.037, and 0.33 Hz for 1, 3, 5, 7, and 10 sec stimulations, respectively [60].

The detection of neuronal activation, in this study, is done using the desired hemodynamic response function (dHRF) [64]. Three gamma functions were utilized to generate the dHRF [60]. To detect the initial dip, dual threshold-based vector phase analysis is used in this study [60]. Four vector components (ΔHbO, ΔHbR, total hemoglobin (ΔHbT), and cerebral oxygen exchange (ΔCOE)) are used as indices to make the vector phase diagram. Fig. 3 shows the visual interpretation of the dual threshold circles on the vector phase diagram. Shaded areas of Phases 7 and 8 are the conventional HR phases, whereas the shaded area in Phases 3, 4, and 5 is the initial dip region.

G. STATISTICAL ANALYSIS

For statistical analysis, t-values, p-values and ΔHbO response of all trials are utilized to find the most active channels. In the present study, t_{crt} was chosen differently for each of the stimuli, according to the degree of freedom for that respective trial period, and the statistical significance level was set to 0.05 for one-tailed t-test. The built-in function *robustfit* by MATLAB ®was used to calculate the t values. A channel was considered to be active if i) p-value < 0.05 and ii) t-value $> t_{crt}$.

III. RESULTS

A. HEMODYNAMIC RESPONCE

It would be ideal if HR is the same for each trial in different brain regions and its characteristics are linear. Assuming the linearity, the concept of dHRF is used to identify the initiation

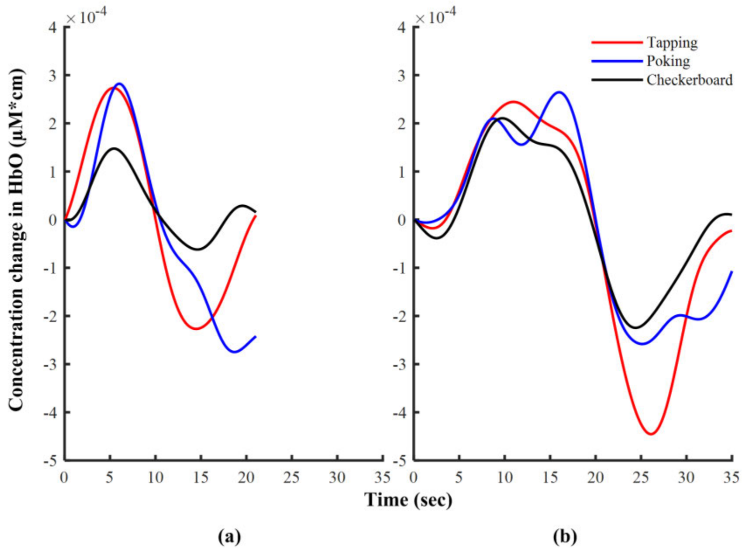

FIGURE 7. Comparison of the hemodynamic responses for three tasks: (a) 1 sec (shortest), (b) 15 sec (longest).

of the real HRs for both short and long stimulation durations in each target area. Fig. 4 depicts the dHRFs that were generated by a three gamma function and stimulation durations in this study. Fig. 5 and Fig. 6 show the averages of ΔHbO and ΔHbR, respectively, evoked by different stimulation durations for all three tasks. The activations in individual brain areas are clearly seen from either short or long stimulation durations.

For individual subjects, the variance is quite high for shorter stimulation intervals, but the average responses across the subjects are quite distinguishable. It is observed that most HRs achieve their peak between 5 sec and 17 sec after the start of stimulation. The maximum value of ΔHbO is observed to occur either during the stimulation or after the end of the stimulation. Fig. 7 compares the responses of the shortest stimulation (1 sec) and the longest stimulation (15 sec). Fig. 8 shows an example of the phase plot (i.e., the trajectories of ΔHbO and ΔHbR) of Sub. 1 drawn in the vector phase diagram (Fig. 3), which can visualize the initial dip phase and the HR phase.

B. COMPAPRISON OF STIMULATION DURATIONS

While comparing the averaged HRs, statistical significant differences (i.e., p-value < 0.0033, after Bonferroni correction) were found among the mean HRs for all the stimulation durations. While comparing the results qualitatively across all the brain areas under observation, somewhat interesting trend in the magnitude of the HR for the average results over all the subjects was observed. For the tapping task, the peak values increased as stimulation intervals increased up to 10 sec, but the peak amplitude of 15 sec stimulation was much lower as compared to others. For the poking task, the magnitudes of the HR responses kept on increasing for the stimulation intervals from 1 sec to 5 sec and then started decreasing for stimulation intervals more than 5 sec. Similarly, for the checkerboard task, the average results showed an increase in the magnitudes of signals for stimulation intervals up to 7 sec, and then decreased in 10 sec and 15 sec stimulation durations. Fig. 9 shows the comparison of HR responses for 1 sec stimulus duration of Subject 1.

A sufficient amount of activation has been seen from most subjects for all three tasks. To check the intra-subject repeatability, 1 sec stimulation duration was checked twice on the subjects. The experiments for this purpose were conducted on different days. Fig. 10 shows the repeatability for 1 sec stimulation duration in all 10 subjects. Table 1 summarizes the repeatability of all channels and all three tasks. Table 2 summarizes the most suitable stimulation durations for various purposes according to the respective tasks.

C. COMPARISON OF TEMPORAL CHARACTERSTICS

Three different temporal characteristics (full width at half maximum (FWHM), time to peak, and peak amplitude) were examined for all the stimulation intervals of all three tasks. One tailed t-test was applied on the obtained temporal characteristics. There was no significant difference between two adjacent durations (i.e., 1 and 3 sec or 3 and 5 sec). However, a significant difference (p-value < 0.05) was observed when comparing the 1 sec (or 3 sec) stimulation duration with a long stimulation duration (i.e., 10 or 15 sec).

Table 3 shows the average values of three temporal features (i.e., FWHM, peak value, time to peak). These three features were selected as they well describe the characteristics of a time-domain signal. However, other time-domain features like slope, mean, etc. can be investigated too. Fig. 11 depicts the overall comparison of the temporal characteristics for ΔHbO responses for the shortest, longest, and the

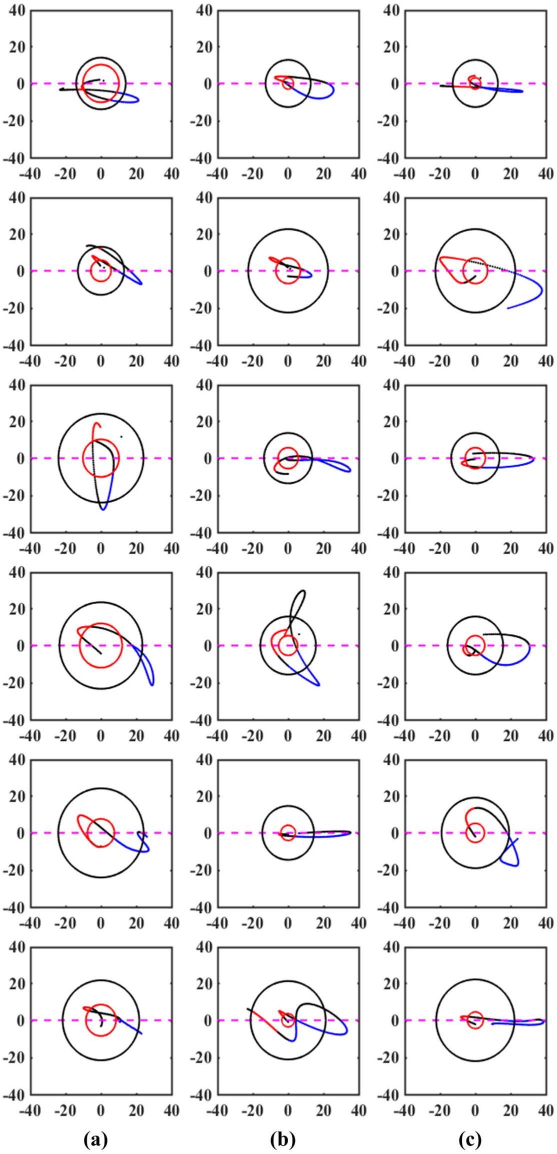

FIGURE 8. Comparison of the trajectories of six different task durations (top: 1 sec, bottom: 15 sec) followed by 10 sec rest: (a) Checkerboard, (b) poking, and (c) tapping, for Subject 1.

intermediate stimulation durations along with their standard deviations. It is observed that the HR for shorter stimulation is narrower and occurs faster as compared with the longer stimulation duration in all the areas under observation. For a stimulation lasting for 1sec, the mean ΔHbO response peaked at almost 5.4 sec for checkerboard task, at 5.3 sec for tapping task and 6 sec for poking task. Across all the brain regions under observation, the HRs had a significantly shorter time-to-peak for tapping task as compared to the poking and checkerboard tasks.

IV. DISCUSSIONS

In this study, we have investigated the temporal variability of HRs (i.e., ΔHbO) in the sensorimotor and visual cortices for three different tasks (i.e., right hand finger tapping, right

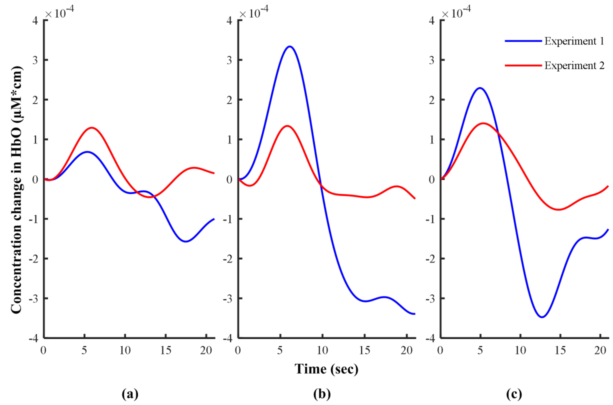

FIGURE 9. Repeatability of HbOs of 1 sec task after one week (Subject 1): (a) Checkerboard, (b) poking, and (c) tapping.

hand finger poking, and checkerboard tasks) with respect to six stimulation durations. The aim is to propose most suitable stimulation periods upon the tasks for the purpose of BCI. To the best of the authors' knowledge, this is the first study to assess the effects of stimulation duration on the HR when fNIRS is used as an imaging tool. As results, the most effective stimulation durations for three tasks are found, and the smallest stimulation durations for detecting the initial dip are suggested.

The obtained findings are summarized as follows:

i) The most interesting finding was observed in the poking task. The initial dip was detected only from the 1 sec poking duration, and it was not observed from any other poking duration (i.e., no initial dip from 3, 5, 7, 10, and 15 sec). Explanations for this are that, first, the HR occurs fast in the poking task (sensory signal) and, second, the increase of ΔHbO surpasses the decrease of ΔHbO caused by neuronal firing if the poking stimulation goes over 1 sec. In the current experiments, the subjects were poked two times for a 1 sec duration. Another explanation could be the insensitivity of the poking stimulation or due to the numbness in the poked area when poking was continued over 1 sec.

ii) It is observed that it takes at least 5 sec for Δ HbO to reach its peak value (for all the stimulation durations) after the onset of a stimulus [65]–[67], which means that the stimuli given within 5 sec are accumulated before the response of the first stimulus reaches its peak value. After attaining the peak value for a long stimulation, ΔHbO sustains its plateau level for a certain period (depending on the stimulation duration) before coming back to the baseline, which was then followed by an undershoot in ΔHbO.

iii) ΔHbO starts to decrease as soon as the stimulation ends, and it takes nearly 12 sec to settle down near to the baseline [68]. Because of this, the inter-stimulation interval needs to be set to more than 20 sec, so that the subsequent stimulation is made after the previous one settled down.

iv) The response caused by a long stimuli duration (i.e., 10 sec or 15 sec) takes comparatively longer time to return to

TABLE 1. Repeatability of all channels according to tasks.

Tasks	Channel number	Stimulation duration (sec)					
		1	3	5	7	10	15
Checkerboard	1	**40.00**	**50.00**	**46.67**	**41.67**	**33.33**	26.67
	2	**46.67**	**46.67**	38.33	**36.67**	**41.67**	**38.33**
	3	**41.67**	**50.00**	**41.67**	31.67	28.33	31.67
	4	**43.33**	31.67	**40.00**	**33.33**	30.00	30.00
	5	**41.67**	**51.67**	**41.67**	25.00	26.67	**36.67**
	6	**41.67**	**41.67**	**38.33**	**36.67**	28.33	26.67
	7	**35.00**	28.33	**35.00**	**41.67**	**38.33**	28.33
	8	**45.00**	**46.67**	**40.00**	**36.67**	**33.33**	26.67
	9	**36.67**	30.00	**40.00**	25.00	30.00	26.67
	10	**33.33**	**36.67**	31.67	**33.33**	28.33	**36.67**
	11	**36.67**	31.67	31.67	**33.33**	**40.00**	15.00
	12	**38.33**	**38.33**	26.67	**35.00**	31.67	23.33
	13	30.00	**36.67**	28.33	23.33	30.00	16.67
	14	30.00	26.67	28.33	16.67	16.67	16.67
	15	**36.67**	23.33	21.67	25.00	20.00	13.33
	16	28.33	23.33	16.67	15.00	8.33	16.67
Poking	17	**46.67**	**45.00**	**45.00**	**43.33**	**35.00**	**46.67**
	18	**53.33**	**40.00**	**40.00**	**48.33**	**35.00**	**43.33**
	19	**65.00**	**50.00**	**41.67**	**43.33**	**58.33**	**43.33**
	20	**43.33**	**60.00**	**45.00**	**40.00**	**35.00**	**48.33**
	21	**36.67**	**50.00**	**45.00**	**48.33**	**38.33**	**36.67**
	22	**53.33**	**46.67**	**38.33**	**41.67**	**41.67**	**36.67**
	23	**43.33**	**40.00**	**46.67**	**56.67**	**41.67**	**36.67**
	24	**50.00**	**50.00**	**45.00**	**46.67**	**38.33**	**45.00**
	25	**46.67**	**53.33**	**36.67**	**51.67**	31.67	**38.33**
	26	**60.00**	**48.33**	**36.67**	**40.00**	31.67	**41.67**
	27	33.33	**40.00**	28.33	20.00	28.33	26.67
	28	**36.67**	31.67	25.00	25.00	23.33	28.33
	29	25.00	25.00	21.67	6.67	13.33	15.00
	30	26.67	26.67	18.33	8.33	11.67	16.67
	31	8.33	5.00	10.00	6.67	1.67	8.33
	32	0.00	3.33	0.00	1.67	3.33	0.00
Tapping	17	**45.00**	**50.00**	**66.67**	**63.33**	**68.33**	**66.67**
	18	**53.33**	**53.33**	**53.33**	**63.33**	**55.00**	**58.33**
	19	38.33	**48.33**	**60.00**	**61.67**	**53.33**	**48.33**
	20	**58.33**	**51.67**	**53.33**	**61.67**	**50.00**	**46.67**
	21	35.00	**51.67**	**60.00**	**55.00**	**61.67**	**46.67**
	22	**48.33**	**55.00**	**51.67**	**70.00**	**63.33**	**60.00**
	23	**51.67**	**46.67**	**66.67**	**65.00**	**55.00**	**43.33**
	24	**45.00**	**48.33**	**63.33**	**71.67**	**63.33**	**46.67**
	25	**60.00**	**50.00**	41.67	**61.67**	**46.67**	**50.00**
	26	**45.00**	38.33	**50.00**	**65.00**	**51.67**	**46.67**
	27	38.33	41.67	40.00	**43.33**	**45.00**	33.33
	28	38.33	38.33	**43.33**	30.00	26.67	31.67
	29	23.33	21.67	33.33	10.00	21.67	21.67
	30	23.33	31.67	31.67	11.67	16.67	23.33
	31	15.00	5.00	6.67	6.67	5.00	11.67
	32	0.00	8.33	0.00	3.33	5.00	0.00

the baseline. Statistical significant differences were observed in the comparisons of the temporal characteristics between the HR of 1 sec and those of 7 ∼ 15 sec stimulation durations. In contrast, no statistical significant difference was found between 1 sec stimulation and 3 sec stimulation. This reveals that 3 sec stimulation might not provide a better result than

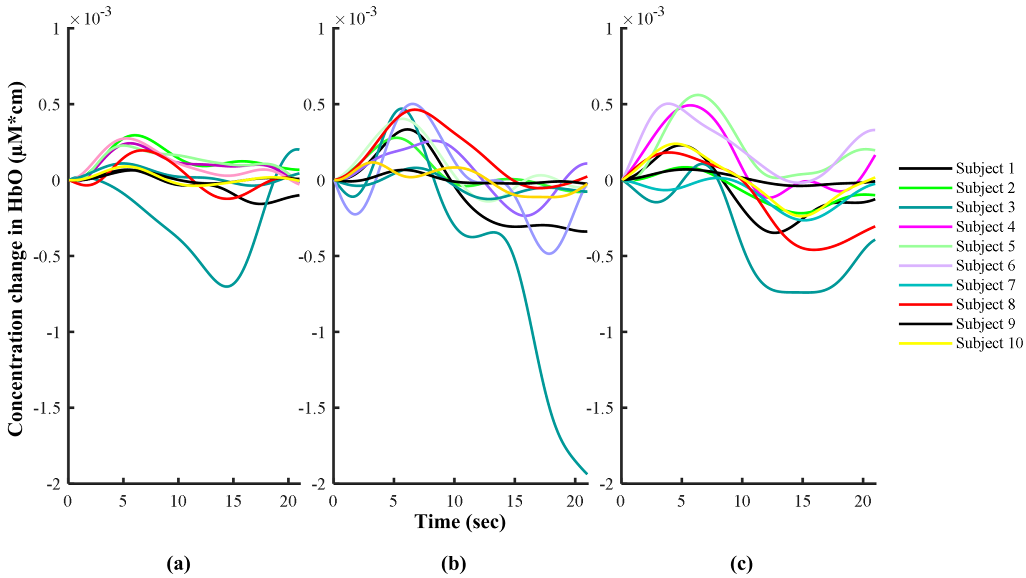

FIGURE 10. Comparison of HbOs for 1 sec task over 10 subjects: (a) Checkerboard, (b) poking, and (c) tapping.

TABLE 2. Stimulation durations suggested for three tasks.

Category	Checkerboard (sec)	Poking (sec)	Tapping (sec)
Best duration to obtain max. ΔHbO	7	5	10
Minimum duration	1	1	1
Minimum duration to get initial dip	3	1	3

TABLE 3. Comparison of the temporal characteristics.

Tasks	Stimulation durations					
	1 sec	3 sec	5 sec	7 sec	10 sec	15 sec
FWHM						
Checkerboard	5.43	5.68	5.72	10.31	7.09	11.06
Tapping	6.38	5.82	5.79	5.02	11.13	12.09
Poking	5.05	6.32	5.22	7.74	9.34	12.11
Peak amplitude ($\times 10^{-4}$)						
Checkerboard	1.47	2.36	2.48	3.12	2.42	0.11
Tapping	2.73	3.63	4.28	4.42	4.74	2.44
Poking	2.82	2.94	3.95	3.71	3.54	2.64
Time to peak						
Checkerboard	5.44	7.10	8.00	11.46	11.78	9.73
Tapping	5.38	6.72	7.42	7.68	9.34	10.94
Poking	6.02	6.85	7.68	8.19	11.46	16.00

1 sec stimulation, and 1 sec stimulation can well serve the purpose of a quick command generation time.

v) The stimulation durations to detect the initial dip are suggested in Table 2, while the full development of them in checkerboard and tapping tasks takes 3 sec.

vi) The stimulation durations that have shown the highest peak are different in three brain cortices. The durations that spawned the maximum values are summarized in Table 2 according to the cortices.

vii) From the experimental results, it is observed that the peak values did not keep increasing with the increase of stimulation durations (whereas the peak value in the dHRF for a longer stimulation duration gets larger than that of a short stimulation duration, because the dHRF is computed by convolving the canonical hemodynamic response function with the stimulation interval). It is seen that the HR achieves its peak value at certain duration: The checkerboard, poking, and tapping tasks achieved their maximum values from the 7 sec, 5 sec, and 10 sec stimulation durations, respectively. After which, a longer stimulation showed a lower peak value. Possible reasons for this are: After certain stimulus duration, the area of activation in the cortex becomes wider and the strength of the signal becomes low resulting in a lower average value. Another explanation could be, for stimulation duration over 10 sec, the subjects become tired or bored (as reported by many subjects), which could be the reason for the low peak value of the 15 sec stimulation interval. However, for 15 sec stimulus, the peak value stayed at its plateau for a certain amount of time.

viii) For checking the stimulation durations having most repeatable channels in Table 1, the mean value for each task was calculated (i.e., checkerboard: 32.4, poking: 34.11, tapping: 42.15). The channels that lie over the mean value are marked in bold face. For the checkerboard task, the 1 sec stimulation duration shows most channels having repeatability over the mean value. For the poking task, 1 and 3 sec

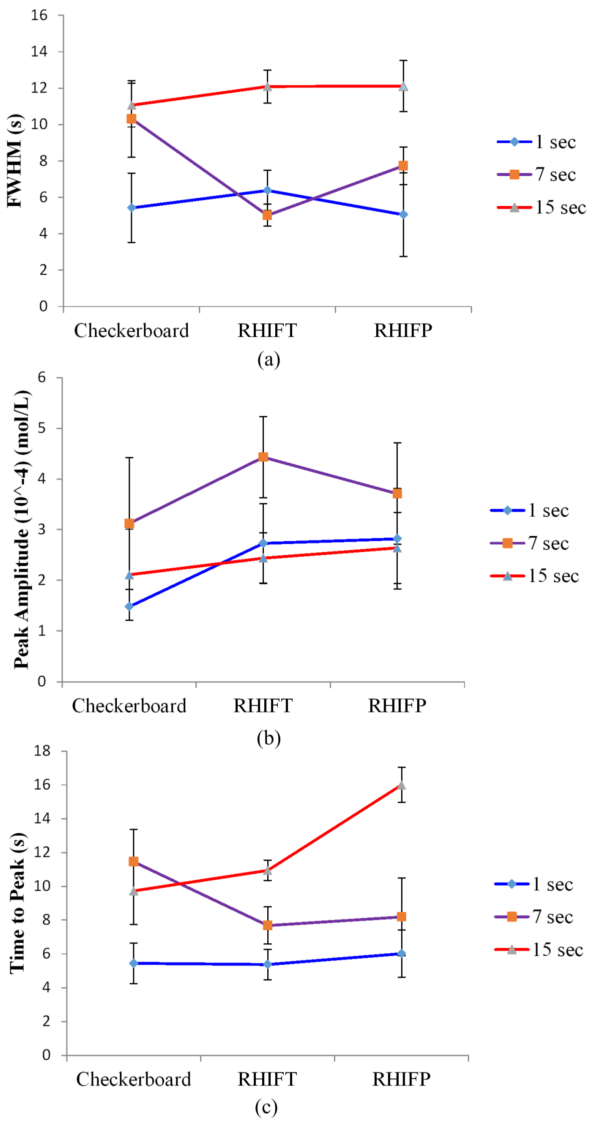

FIGURE 11. **Temporal characteristics for the shortest (1 sec), intermediate (7 sec) and longest (15 sec) stimulation durations. (a) FWHMs, (b) peak amplitude, and (c) time to peak.**

stimulation durations, and similarly for tapping task, 7 and 10 sec stimulation durations had most channels having repeatability over their mean values, respectively. The results suggest that these stimulation durations can result in the most activated channels for the three tasks. While comparing the results between fNIRS and fMRI, certain aspects need to be considered from the effects of stimulation duration on HRs. Most important factor is that the number of channels in fNIRS is quite limited compared to fMRI, which depends on the number of optodes in the fNIRS case [69].

In this study, the subjects were not prohibited from the use of caffeine. The nearby noise was reduced, but unfortunately was not completely controlled. Alongside these factors, the boredom from sitting idle for longer durations in a completely dark room and from the repetition of the task could have contributed to the level of attention the subject was paying to the experiment. Similarly, few subjects reported that they were facing difficulty while keeping themselves awake during the experiment. This issue can be addressed in further studies by giving a ready queue 1 sec before the start of stimulation so that the subject becomes attentive to the task to be performed, as 1 sec stimulation duration is instantaneous and the subject must be paying full attention. Another limitation of this study is that all the participants were healthy male individuals and all had right dominant hand. While discussing the repeatability of the tasks, these limitations might cater for some error in the results [70]. Also, the current study focused on only popular three tasks found in the literature, but more interesting tasks would be flickering signals, mental tasks, touching tasks, etc. for reactive/active BCIs. In future studies, more diverse tasks and brain areas need to be explored.

In this study, it was observed that a suitable level of sensitivity to stimulation duration is attainable from all the brain areas. This makes fNIRS-based brain imaging a feasible tool to study activations in both the sensorimotor and visual cortices even for shorter stimulation durations like 1 sec. The accomplishment with healthy subjects can enable an extension of the work to study the dysfunction of the sensory, visual or motor pathways using fNIRS making a ground for the comparison. Further studies need to be conducted using a dense optode arrangement to spatially specify the origin of the signals.

This might make the signal quality much better to be used for individual subject analysis. As future work, integration of control techniques [71]–[73] in a BCI framework can improve the neuro-feedback performance. In this work, the examined stimulation durations of 1, 3, 5, 7, 10, and 15 sec were chosen upon the authors' experience and the amount of experiments to be made. However, in a future study, more fine stimulation durations (like 0.2 sec incremental intervals instead of 1, 3, 5, 7, and 10 durations) has to be checked to further refine the shortest and best stimulation durations.

V. CONCLUSION

This paper made a big step towards standardizing the stimulation duration for the purpose of functional near-infrared spectroscopy (fNIRS)-based brain-computer interface (BCI). The simultaneous monitoring of different brain cortices for randomly occurring different tasks solved the glitches encountered with the orthodox approaches for selection of stimulation duration for healthy individuals. In the present study, most effective stimulation durations were chosen from the six durations tested on three brain areas; visual, sensory, and motor cortices. The use of 7, 5 and 10 sec stimulation durations for checkerboard, poking and tapping tasks, respectively, are suggested for the purpose of fNIRS-based BCI. Also, the phenomena of initial dip can be easily detected using smaller stimulation durations. Therefore, if the goal is to detect initial dips, 1 sec stimulation duration can be used causing necessary amount of activation. On the other hand, if the goal is to use the HR activation or the same stimulus duration for all the brain cortices, 1 second stimulation interval can provide significant activation of the brain. Since there is a long way to go for fNIRS to be used for clinical usages, making a standardization committee in the fNIRS community is suggested.

AUTHOR CONTRIBUTION

MNAK conducted experiments, carried out the data processing, and wrote the first draft of the manuscript. MRB verified the data analyses in the revision process. K-SH has suggested the theoretical aspects of the study, corrected the manuscript, and supervised all the process from the beginning. All the authors have approved the final manuscript.

REFERENCES

[1] J. R. Wolpaw, N. Birbaumer, D. J. McFarland, G. Pfurtscheller, and T. M. Vaughan, "Brain–computer interfaces for communication and control," *Clin. Neurophysiol.*, vol. 113, no. 6, pp. 767–791, 2002.

[2] A. Zafar and K.-S. Hong, "Detection and classification of three-class initial dips from prefrontal cortex," *Biomed. Opt. Express*, vol. 8, no. 1, pp. 367–383, Jan. 2017.

[3] X. Xu, Y. Zhang, M. Tang, H. Gu, S. Yan, and J. Yang, "Emotion recognition based on double tree complex wavelet transform and machine learning in Internet of Things," *IEEE Access*, vol. 7, pp. 154114–154120, 2019.

[4] H. Lee, J. Choi, S. Kim, S. C. Jun, and B.-G. Lee, "A compressive sensing-based automatic sleep-stage classification system with radial basis function neural network," *IEEE Access*, vol. 7, pp. 186499–186509, 2019.

[5] T. Piotrowski, J. Nikadon, and D. Gutierrez, "MV-PURE spatial filters with application to EEG/MEG source reconstruction," *IEEE Trans. Signal Process.*, vol. 67, no. 3, pp. 553–567, Feb. 2019.

[6] K.-S. Hong and M. A. Yaqub, "Application of functional near-infrared spectroscopy in the healthcare industry: A review," *J. Innov. Opt. Health Sci.*, vol. 12, no. 6, Nov. 2019, Art. no. 1930012.

[7] N. Naseer and K.-S. Hong, "FNIRS-based brain-computer interfaces: A review," *Frontiers Hum. Neurosci.*, vol. 9, Jan. 2015, Art. no. 172.

[8] A. Zafar and K.-S. Hong, "Reduction of onset delay in functional near-infrared spectroscopy: Prediction of HbO/HbR signals," *Frontiers Neurorobot.*, vol. 14, Feb. 2020, Art. no. 10.

[9] T. K. K. Ho, J. Gwak, C. M. Park, and J.-I. Song, "Discrimination of mental workload levels from multi-channel fNIRS using deep leaning-based approaches," *IEEE Access*, vol. 7, pp. 24392–24403, 2019.

[10] D. Liu, B. Wang, T. Pan, J. Li, Z. Qin, L. Zhang, Z. Zhou, and F. Gao, "Toward quantitative near infrared brain functional imaging: Lock-in photon counting instrumentation combined with tomographic reconstruction," *IEEE Access*, vol. 7, pp. 86829–86842, 2019.

[11] L. Li, X. Pan, H. Yang, T. Zhang, and Z. Liu, "Supervised dictionary learning with regularization for near-infrared spectroscopy classification," *IEEE Access*, vol. 7, pp. 100923–100932, 2019.

[12] A.-K. Seghouane and D. Ferrari, "Robust hemodynamic response function estimation from fNIRS signals," *IEEE Trans. Signal Process.*, vol. 67, no. 7, pp. 1838–1848, Apr. 2019.

[13] C. Enzinger, S. Ropele, F. Fazekas, M. Loitfelder, F. Gorani, T. Seifert, G. Reiter, C. Neuper, G. Pfurtscheller, and G. Müller-Putz, "Brain motor system function in a patient with complete spinal cord injury following extensive brain–computer interface training," *Express Brain Res.*, vol. 190, pp. 215–223, Jul. 2008.

[14] E. Buch, C. Weber, L. G. Cohen, C. Braun, M. A. Dimyan, T. Ard, J. Mellinger, A. Caria, S. Soekadar, A. Fourkas, and N. Birbaumer, "Think to move: A neuromagnetic brain-computer interface (BCI) system for chronic stroke," *Stroke*, vol. 39, no. 3, pp. 910–917, Mar. 2008.

[15] S. H. Sardouie and M. B. Shamsollahi, "Selection of efficient features for discrimination of hand movements from MEG using a BCI competition IV data set," *Frontiers Neurosci.*, vol. 6, Apr. 2012, Art. no. 42.

[16] A. Pellicer and M. D. C. Bravo, "Near-infrared spectroscopy: A methodology-focused review," *Seminars Fetal Neonatal Med.*, vol. 16, no. 1, pp. 42–49, Feb. 2011.

[17] H. Santosa, M. Jiyoun Hong, S.-P. Kim, and K.-S. Hong, "Noise reduction in functional near-infrared spectroscopy signals by independent component analysis," *Rev. Sci. Instrum.*, vol. 84, no. 7, Jul. 2013, Art. no. 073106.

[18] M. Cope and D. T. Delpy, "System for long-term measurement of cerebral blood and tissue oxygenation on newborn infants by near infra-red transillumination," *Med. Biol. Eng. Comput.*, vol. 26, no. 3, pp. 289–294, May 1988.

[19] F. Montani, A. Oliynyk, and L. Fadiga, "Superlinear summation of information in premotor neuron pairs," *Int. J. Neural Syst.*, vol. 27, no. 2, Mar. 2017, Art. no. 1650009.

[20] A. Villringer, J. Planck, C. Hock, L. Schleinkofer, and U. Dirnagl, "Near infrared spectroscopy (NIRS): A new tool to study hemodynamic changes during activation of brain function in human adults," *Neurosci. Lett.*, vol. 154, nos. 1–2, pp. 101–104, May 1993.

[21] H. Watanabe, Y. Shitara, Y. Aoki, T. Inoue, S. Tsuchida, N. Takahashi, and G. Taga, "Hemoglobin phase of oxygenation and deoxygenation in early brain development measured using fNIRS," *Proc. Nat. Acad. Sci. USA*, vol. 114, no. 9, pp. E1737–E1744, Feb. 2017.

[22] S. Cutini, S. B. Moro, and S. Bisconti, "Functional near infrared optical imaging in cognitive neuroscience: An introductory review," *J. Near Infr. Spectrosc.*, vol. 20, no. 1, pp. 75–92, Feb. 2012.

[23] U. Ghafoor, J.-H. Lee, K.-S. Hong, S.-S. Park, J. Kim, and H.-R. Yoo, "Effects of acupuncture therapy on MCI patients using functional near-infrared spectroscopy," *Frontiers Aging Neurosci.*, vol. 11, Aug. 2019, Art. no. 237.

[24] Z. Wang, D. Ming, Y. Zhou, L. Chen, B. Gu, W. Yi, S. Liu, M. Xu, H. Qi, and F. He, "BCI monitor enhances electroencephalographic and cerebral hemodynamic activations during motor training," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 27, no. 4, pp. 780–787, Apr. 2019.

[25] P. C. Petrantonakis and I. Kompatsiaris, "Single-trial NIRS data classification for brain–computer interfaces using graph signal processing," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 26, no. 9, pp. 1700–1709, Sep. 2018.

[26] Y. Zheng, D. Zhang, L. Wang, Y. Wang, H. Deng, S. Zhang, D. Li, and D. Wang, "Resting-state-based spatial filtering for an fNIRS-based motor imagery brain-computer interface," *IEEE Access*, vol. 7, pp. 120603–120615, 2019.

[27] M. A. Tanveer, M. J. Khan, M. J. Qureshi, N. Naseer, and K.-S. Hong, "Enhanced drowsiness detection using deep learning: An fNIRS study," *IEEE Access*, vol. 7, pp. 137920–137929, 2019.

[28] T. Zhu, Y. Zhou, Z. Xia, J. Dong, and Q. Zhao, "Progressive filtering approach for early human action recognition," *Int. J. Control, Autom. Syst.*, vol. 16, no. 5, pp. 2393–2404, Oct. 2018.

[29] J. Moon, H. Kim, and B. Lee, "View-point invariant 3D classification for mobile robots using a convolutional neural network," *Int. J. Control, Autom. Syst.*, vol. 16, no. 6, pp. 2888–2895, Dec. 2018.

[30] M. Yazdani, H. Salarieh, and M. S. Foumani, "Bio-inspired decentralized architecture for walking of a 5-link biped robot with compliant knee joints," *Int. J. Control, Autom. Syst.*, vol. 16, no. 6, pp. 2935–2947, Dec. 2018.

[31] H.-D. Nguyen and K.-S. Hong, "Bundled-optode implementation for 3D imaging in functional near-infrared spectroscopy," *Biomed. Opt. Express*, vol. 7, no. 9, p. 3491, Sep. 2016.

[32] U. Ghafoor, S. Kim, and K.-S. Hong, "Selectivity and longevity of peripheral-nerve and machine interfaces: A review," *Frontiers Neurorobot.*, vol. 11, Oct. 2017, Art. no. 59.

[33] K.-S. Hong and N. Naseer, "Reduction of delay in detecting initial dips from functional near-infrared spectroscopy signals using vector-based phase analysis," *Int. J. Neural Syst.*, vol. 26, no. 3, May 2016, Art. no. 1650012.

[34] K.-S. Hong and A. Zafar, "Existence of initial dip for BCI: An illusion or reality," *Frontiers Neurorobot.*, vol. 12, Oct. 2018, Art. no. 69.

[35] D. A. Boas, C. E. Elwell, M. Ferrari, and G. Taga, "Twenty years of functional near-infrared spectroscopy: Introduction for the special issue," *NeuroImage*, vol. 85, pp. 1–5, Jan. 2014.

[36] F. Scholkmann, S. Kleiser, A. J. Metz, R. Zimmermann, J. M. Pavia, U. Wolf, and M. Wolf, "A review on continuous wave functional near-infrared spectroscopy and imaging instrumentation and methodology," *NeuroImage*, vol. 85, pp. 6–27, Jan. 2014.

[37] J. Shin, J. Kwon, J. Choi, and C.-H. Im, "Ternary near-infrared spectroscopy brain-computer interface with increased information transfer rate using prefrontal hemodynamic changes during mental arithmetic, breath-holding, and idle state," *IEEE Access*, vol. 6, pp. 19491–19498, 2018.

[38] L. Becerra, W. Harris, D. Joseph, T. Huppert, D. A. Boas, and D. Borsook, ''Diffuse optical tomography of pain and tactile stimulation: Activation in cortical sensory and emotional systems,'' *NeuroImage*, vol. 41, no. 2, pp. 252–259, Jun. 2008.
[39] L. Becerra, W. Harris, M. Grant, E. George, D. Boas, and D. Borsook, ''Diffuse optical tomography activation in the somatosensory cortex: Specific activation by painful vs. non-painful thermal stimuli,'' *PLoS ONE*, vol. 4, no. 11, 2009, Art. no. e8016.
[40] M. A. Yaqub, S.-W. Woo, and K.-S. Hong, ''Effects of HD-tDCS on resting-state functional connectivity in the prefrontal cortex: An fNIRS study,'' *Complexity*, vol. 2018, Nov. 2018, Art. no. 1613402.
[41] M. A. Yücel, C. M. Aasted, M. P. Petkov, D. Borsook, D. A. Boas, and L. Becerra, ''Specificity of hemodynamic brain responses to painful stimuli: A functional near-infrared spectroscopy study,'' *Sci. Rep.*, vol. 5, no. 1, Aug. 2015, Art. no. 9469.
[42] N. Üceyler, J. Zeller, S. Kewenig, S. Kittel-Schneider, A. J. Fallgatter, and C. Sommer, ''Increased cortical activation upon painful stimulation in fibromyalgia syndrome,'' *BMC Neurol.*, vol. 15, no. 1, Dec. 2015, Art. no. 210.
[43] X.-S. Hu, K.-S. Hong, and S. S. Ge, ''Recognition of stimulus-evoked neuronal optical response by identifying chaos levels of near-infrared spectroscopy time series,'' *Neurosci. Lett.*, vol. 504, no. 2, pp. 115–120, Oct. 2011.
[44] P. Wobst, R. Wenzel, M. Kohl, H. Obrig, and A. Villringer, ''Linear aspects of changes in deoxygenated hemoglobin concentration and cytochrome oxidase oxidation during brain activation,'' *NeuroImage*, vol. 13, no. 3, pp. 520–530, Mar. 2001.
[45] L. M. Ward, R. T. Aitchison, M. Tawse, A. J. Simmers, and U. Shahani, ''Reduced haemodynamic response in the ageing visual cortex measured by absolute fNIRS,'' *PLoS ONE*, vol. 10, no. 4, 2015, Art. no. e0125012.
[46] S. Wijeakumar, U. Shahani, W. A. Simpson, and D. L. McCulloch, ''Localization of hemodynamic responses to simple visual stimulation: An fNIRS study,'' *Investigative Opthalmol. Vis. Sci.*, vol. 53, no. 4, pp. 2266–2273, Apr. 2012.
[47] G. M. Boynton, S. A. Engel, G. H. Glover, and D. J. Heeger, ''Linear systems analysis of functional magnetic resonance imaging in human V1,'' *J. Neurosci.*, vol. 16, no. 13, pp. 4207–4221, Jul. 1996.
[48] A. L. Vazquez and D. C. Noll, ''Nonlinear aspects of the BOLD response in functional MRI,'' *NeuroImage*, vol. 7, no. 2, pp. 108–118, Feb. 1998.
[49] H.-L. Liu and J.-H. Gao, ''An investigation of the impulse functions for the nonlinear BOLD response in functional MRI,'' *Magn. Reson. Imag.*, vol. 18, no. 8, pp. 931–938, Oct. 2000.
[50] D. A. Soltysik, K. K. Peck, K. D. White, B. Crosson, and R. W. Briggs, ''Comparison of hemodynamic response nonlinearity across primary cortical areas,'' *NeuroImage*, vol. 22, no. 3, pp. 1117–1127, Jul. 2004.
[51] M. D. Robson, J. L. Dorosz, and J. C. Gore, ''Measurements of the temporal fMRI response of the human auditory cortex to trains of tones,'' *NeuroImage*, vol. 7, no. 3, pp. 185–198, Apr. 1998.
[52] L. D. Lewis, K. Setsompop, B. R. Rosen, and J. R. Polimeni, ''Stimulus-dependent hemodynamic response timing across the human subcortical-cortical visual pathway identified through high spatiotemporal resolution 7T fMRI,'' *NeuroImage*, vol. 181, pp. 279–291, Nov. 2018.
[53] S. Weder, X. Zhou, M. Shoushtarian, H. Innes-Brown, and C. McKay, ''Cortical processing related to intensity of a modulated noise stimulus—A functional near-infrared study,'' *J. Assoc. Res. Otolaryngol.*, vol. 19, no. 3, pp. 273–286, Jun. 2018.
[54] N. H. Kashou and B. M. Giacherio, ''Stimulus and optode placement effects on functional near-infrared spectroscopy of visual cortex,'' *Neurophotonics*, vol. 3, no. 2, Jun. 2016, Art. no. 025005.
[55] F. Tian, B. Chance, and H. Liu, ''Investigation of the prefrontal cortex in response to duration-variable anagram tasks using functional near-infrared spectroscopy,'' *J. Biomed. Opt.*, vol. 14, no. 5, 2009, Art. no. 054016.
[56] L. L. Emberson, G. Cannon, H. Palmeri, J. E. Richards, and R. N. Aslin, ''Using fNIRS to examine occipital and temporal responses to stimulus repetition in young infants: Evidence of selective frontal cortex involvement,'' *Develop. Cognit. Neurosci.*, vol. 23, pp. 26–38, Feb. 2017.
[57] L. Sullivan. Power and Sample Size Determination. Boston University of Public Health. Accessed: Feb. 2020. [Online]. Available: http://sphweb.bumc.bu.edu/otlt/MPH-Modules/BS/BS704_Power/BS704_Power_print.html
[58] B. Christie, ''Doctors revise declaration of Helsinki,'' *Brit. Med. J.*, vol. 321, no. 7266, Oct. 2000, Art. no. 913.
[59] D. T. Delpy, M. Cope, P. V. D. Zee, S. Arridge, S. Wray, and J. Wyatt, ''Estimation of optical pathlength through tissue from direct time of flight measurement,'' *Phys. Med. Biol.*, vol. 33, no. 12, Dec. 1988, Art. no. 1433.
[60] A. Zafar and K.-S. Hong, ''Neuronal activation detection using vector phase analysis with dual threshold circles: A functional near-infrared spectroscopy study,'' *Int. J. Neural Syst.*, vol. 28, no. 10, Dec. 2018, Art. no. 1850031.
[61] T. Fekete, D. Rubin, J. M. Carlson, and L. R. Mujica-Parodi, ''The NIRS analysis package: Noise reduction and statistical inference,'' *PLoS ONE*, vol. 6, no. 9, 2011, Art. no. e24322.
[62] J. M. Kainerstorfer, A. Sassaroli, K. T. Tgavalekos, and S. Fantini, ''Cerebral autoregulation in the microvasculature measured with near-infrared spectroscopy,'' *J. Cerebral Blood Flow Metabolism*, vol. 35, no. 6, pp. 959–966, Jun. 2015.
[63] M. J. Khan and K.-S. Hong, ''Hybrid EEG–fNIRS-based eight-command decoding for BCI: Application to quadcopter control,'' *Frontiers Neurorobot.*, vol. 11, Feb. 2017, Art. no. 6.
[64] K.-S. Hong and H.-D. Nguyen, ''State-space models of impulse hemodynamic responses over motor, somatosensory, and visual cortices,'' *Biomed. Opt. Express*, vol. 5, no. 6, pp. 1778–1798, Jun. 2014.
[65] W. N. J. M. Colier, V. Quaresima, R. Wenzel, M. C. van der Sluijs, B. Oeseburg, M. Ferrari, and A. Villringer, ''Simultaneous near-infrared spectroscopy monitoring of left and right occipital areas reveals contra-lateral hemodynamic changes upon hemi-field paradigm,'' *Vis. Res.*, vol. 41, no. 1, pp. 97–102, Jan. 2001.
[66] M. A. McIntosh, U. Shahani, R. G. Boulton, and D. L. McCulloch, ''Absolute quantification of oxygenated hemoglobin within the visual cortex with functional near infrared spectroscopy (fNIRS),'' *Investigative Opthalmol. Vis. Sci.*, vol. 51, no. 9, pp. 4856–4860, Sep. 2010.
[67] S. Wijeakumar, U. Shahani, D. L. McCulloch, and W. A. Simpson, ''Neural and vascular responses to fused binocular stimuli: A VEP and fNIRS study,'' *Investigative Opthalmol. Vis. Sci.*, vol. 53, no. 9, pp. 5881–5889, Aug. 2012.
[68] R. Wenzel, P. Wobst, H. H. Heekeren, K. K. Kwong, S. A. Brandt, M. Kohl, H. Obrig, U. Dirnagl, and A. Villringer, ''Saccadic suppression induces focal hypooxygenation in the occipital cortex,'' *J. Cerebral Blood Flow Metabolism*, vol. 20, no. 7, pp. 1103–1110, Jul. 2000.
[69] F. Tian, G. Alexandrakis, and H. Liu, ''Optimization of probe geometry for diffuse optical brain imaging based on measurement density and distribution,'' *Appl. Opt.*, vol. 48, no. 13, pp. 2496–2504, May 2009.
[70] D. R. Leff, F. Orihuela-Espina, C. E. Elwell, T. Athanasiou, D. T. Delpy, A. W. Darzi, and G.-Z. Yang, ''Assessment of the cerebral cortex during motor task behaviours in adults: A systematic review of functional near infrared spectroscopy (fNIRS) studies,'' *NeuroImage*, vol. 54, no. 4, pp. 2922–2936, Feb. 2011.
[71] Q. C. Nguyen, M. Piao, and K.-S. Hong, ''Multivariable adaptive control of the rewinding process of a roll-to-roll system governed by hyperbolic partial differential equations,'' *Int. J. Control, Autom. Syst.*, vol. 16, no. 5, pp. 2177–2186, Oct. 2018.
[72] K.-S. Hong and P.-T. Pham, ''Control of axially moving systems: A review,'' *Int. J. Control, Autom. Syst.*, vol. 17, no. 12, pp. 2983–3008, Dec. 2019.
[73] Z. Hu, Y. Wang, G. Cui, and D. Zhang, ''Enhance transparency of force feedback interaction series mechanism by SMC strategy,'' *Int. J. Control, Autom. Syst.*, vol. 17, no. 7, pp. 1738–1750, Jul. 2019.

M. N. AFZAL KHAN received the B.S. degree in mechatronics engineering from Air University, Islamabad, Pakistan, in 2017. He is currently pursuing the Ph.D. degree with the School of Mechanical Engineering, Pusan National University, Busan, South Korea. His research interests include brain–computer interface, machine learning, brain-controlled robotics, and fNIRS-based brain imaging.

M. RAHEEL BHUTTA received the B.Eng. degree in computer engineering from the COMSATS Institute of Information Technology, Islamabad, Pakistan, in 2003, and the M.Eng. degree in VLSI system design from Griffith University, Australia, in 2005, and the Ph.D. degree from the Department of Cogno-Mechatronics Engineering, Pusan National University, South Korea, in 2017. He is currently an Assistant Professor with the Department of Computer Science and Engineering, Sejong University, Seoul, South Korea. He is currently working on a lie detection system using neuronal and physiological signals, funded by the National Research Foundation of Korea. His research interests include embedded system design, classification and pattern recognition, artificial intelligence, machine learning, multimodal neuroimaging, and brain–computer interfaces.

KEUM-SHIK HONG (Fellow, IEEE) received the B.S. degree in mechanical design and production engineering from Seoul National University, in 1979, the M.S. degree in mechanical engineering from Columbia University, New York, in 1987, the M.S. degree in applied mathematics from the University of Illinois at Urbana-Champaign (UIUC), and the Ph.D. in mechanical engineering from UIUC, in 1991. He joined the School of Mechanical Engineering, Pusan National University (PNU), in 1993. His Integrated Dynamics and Control Engineering Laboratory was designated a National Research Laboratory by the Ministry of Science and Technology of Korea, in 2003. In 2009, under the auspices of the World Class University Program of the Ministry of Education, Science and Technology (MEST) of Korea, he established the Department of Cogno-Mechatronics Engineering, PNU. His current research interests include brain–computer interface, nonlinear systems theory, adaptive control, distributed parameter systems, autonomous vehicles, and innovative control applications in brain engineering. He was a past President of the Institute of Control, Robotics and Systems (ICROS), South Korea, and the President of Asian Control Association. Dr. Hong is a Fellow of the Korean Academy of Science and Technology, an ICROS Fellow, a member of the National Academy of Engineering of Korea, and many other societies. He has received many awards including the Best Paper Award from the KFSTS of Korea in 1999, the F. Harashima Mechatronics Award in 2003, the IJCAS Scientific Activity Award in 2004, the Automatica Certificate of Outstanding Service in 2006, the Presidential Award of Korea in 2007, the ICROS Achievement Award in 2009, the IJCAS Contribution Award in 2010, the Premier Professor Award in 2011, the JMST Contribution Award in 2011, the IJCAS Contribution Award in 2011, the IEEE Academic Award of ICROS in 2016, etc. He was the Organizing Chair of the ICROS-SICE International Joint Conference 2009, Fukuoka, Japan. He served as an Associate Editor of *Automatica* from 2000 to 2006, as an Editor-in-Chief of the *Journal of Mechanical Science and Technology* from 2008 to 2011, and is serving as an Editor-in-Chief of the *International Journal of Control, Automation, and Systems*.