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Research report

Single-trial classification of near-infrared spectroscopy signals arising from multiple cortical regions

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HIGHLIGHTS

- To classify non-motor tasks via NIRS, the prefrontal cortex has primarily been used.
- We classified NIRS signals measured from both the prefrontal and parietal cortices.
- Average binary classification accuracies exceeded 80% across 11 participants.
- Inclusion of parietal measurements significantly improved classification accuracies.
- Exploiting multiple brain regions can improve brain state classification with NIRS.

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ABSTRACT

Near-infrared spectroscopy (NIRS) brain–computer interface (BCI) studies have primarily made use of measurements taken from a single cortical area. In particular, the anterior prefrontal cortex has been the key area used for detecting higher-level cognitive task performance. However, mental task execution typically requires coordination between several, spatially-distributed brain regions. We investigated the value of expanding the area of interrogation to include NIRS measurements from both the prefrontal and parietal cortices to decode mental states. Hemodynamic activity was monitored at 46 locations over the prefrontal and parietal cortices using a continuous-wave near-infrared spectrometer while 11 able-bodied adults rested or performed either the verbal fluency task (VFT) or Stroop task. Offline classification was performed for the three possible binary problems using 25 iterations of bagging with a linear discriminant base classifier. Classifiers were trained on a 10 dimensional feature set. When all 46 measurement locations were considered for classification, average accuracies of $80.4 \pm 7.0\%$, $82.4 \pm 7.6\%$, and $82.8 \pm 5.9\%$ in differentiating VFT *vs* rest, Stroop *vs* rest and VFT *vs* Stroop, respectively, were obtained. Relative to using measurements from the anterior PFC alone, an overall average improvement of 11.3% was achieved. Utilizing NIRS measurements from the prefrontal and parietal cortices can be of value in classifying mental states involving working memory and attention. NIRS-BCI accuracies may be improved by incorporating measurements from several, distinct cortical regions, rather than a single area alone. Further development of an NIRS-BCI supporting combinations of VFT, Stroop task and rest states is also warranted.

1. Introduction

1.1. NIRS-BCIs

Control of a brain–computer interface (BCI) does not rely on motor movements. Consequently, BCIs can be used to establish a channel of communication for individuals with severe motor impairments. Potential BCI users include individuals with amyotrophic lateral sclerosis, spinal cord injury, or quadriplegic cerebral palsy [1]. A variety of brain-monitoring modalities have been considered for establishing a brain-device pathway, among them is near-infrared spectroscopy (NIRS).

NIRS is an optical imaging modality that non-invasively measures blood oxygenation levels within the cerebral cortex. When an individual performs a cognitive task, the brain areas involved typically require a heightened level of oxygen. This increased metabolic demand is met by an augmented supply of blood, which in turn,

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alters the level of cerebral oxygenation. Consequently, changes in one's mental state can be detected using NIRS and exploited in a BCI. Cerebral oxygenation can be modulated intentionally by, for example, performing a specific mental task, and subsequently translated into an output for controlling an external device.

1.2. Cortical regions considered in NIRS-BCI applications

There is growing evidence supporting the feasibility of establishing an effective NIRS-based BCI. This imaging modality has been used to detect the performance of a variety of controlled mental tasks including motor imagery tasks [2–4] and higher-order cognitive tasks [4–14] using measurements from the motor and prefrontal cortices, respectively. Individuals with congenital or long-term motor impairments may find it difficult or impossible to elicit a significant response in the motor cortex [15–17]. Thus, cognitive tasks that are not motor-based may be more suitable for a larger variety of potential BCI users and will be the focus of this work. These types of tasks previously considered for NIRS-BCI control have included mental arithmetic [4,5,7,8,10–12,14], mental singing [6–8,14], word generation [9,12], mental rotation [12,14], and the n-back task [13].

To detect the performance of higher-level cognitive tasks, the anterior prefrontal cortex (PFC) (BA10) has been a popular area of the brain to monitor [5–13,18]. This brain region is involved in many executive processes such as working memory, attention and decision-making, which are often invoked during a variety of cognitive tasks. Furthermore, the anterior PFC is favorably situated underneath the forehead, an area free from hair.

Although successful differentiation of two mental states using measurements exclusively from the anterior PFC has been demonstrated [5–13], cognitive processes typically involve coordination between several, spatially-distributed brain regions. Thus, considering cortical activity measured from multiple brain regions may potentially improve the accuracy and rate at which mental states are decoded.

In classifying higher-level cognitive tasks, a limited number of NIRS studies have considered measurements from brain regions other than or in addition to the anterior PFC [4,5,14]. To differentiate mental arithmetic and rest, Bauernfeind et al. measured cortical activity from both the anterior and dorsolateral prefrontal cortices [5]. By considering activity from the left or right dorsolateral PFC in combination with that of the anterior PFC, classification accuracies significantly improved beyond those attained with signals from any of the three regions alone. Results of this work suggest that using information from more than just a single region in the PFC can improve the differentiation of mental states. Further improvements in discriminatory power may be achievable by also considering brain regions outside of the PFC.

Although single-trial classification studies using NIRS have focused primarily on the anterior prefrontal and motor cortices, functional activity has also been detected successfully in other brain regions using NIRS in non-BCI studies. These regions include the dorsolateral PFC [19–21], temporal lobe [19,20], parietal lobe [21,22], and occipital lobe [23].

1.3. Brain regions engaged in higher-level cognitive task performance

Many higher-level cognitive tasks suitable for NIRS-BCI control rely on executive processes such as working memory, problem-solving, and attention. Tasks involving this type of information processing often engage the frontal and parietal brain regions [24–26] since these areas are key components of the brain's attentional network [27]. The verbal fluency task (VFT) and Stroop task are examples of such tasks.

1.3.1. Verbal fluency task

The VFT is a verbal working memory task and has been used in previous NIRS work [9,12,19,20]. The task entails the retrieval of words associated by a common criterion, from memory and without repetition. The letter fluency version of the VFT requires an individual to generate as many words as possible beginning with the same letter. Covert performance of the VFT for NIRS-BCI control has previously been explored [9,12]. In [9], the VFT was differentiated from a controlled resting state at an average accuracy of 76.1 ± 8.4% across nine participants using nine measurements from the anterior PFC. In [12], VFT *vs* rest was classified at an average accuracy of 70% across 10 participants using eight prefrontal measurements.

Because the VFT engages one's verbal working memory, functional studies have found that it relies on a distributed network that includes frontal and parietal brain regions. The individual must use their working memory to recall words and inhibit repetition or inappropriate responses, inducing activity in the anterior PFC (BA10) [9,12,20]. Cortical regions in the left frontal hemisphere involved in the planning and production of speech and word representation are also often activated during VFT performance. These areas include the dorsolateral PFC (BA9, BA46) [28,29] ventrolateral PFC (BA44, BA45) [19,20,28,30,31], and the premotor area (BA6) [30,31]. Lastly, the VFT can induce activity in the left inferior parietal cortex (BA 39, BA 40) [29,30] due to this brain region's involvement in attention, information processing, and working memory.

1.3.2. Stroop task

The Stroop task is often used to assess one's selective attention. In the colour-word variant of this task, an individual is presented with a word stimulus and must identify the colour of the ink in which the word is written. For example, if the word 'RED' is printed in blue ink, the individual must identify that the word is written in *blue*, and must inhibit the more intuitive response of reading the word *red*.

The Stroop paradigm involves one's attentional resources and behavioral inhibition, while placing minimal demand on one's working memory [32]. Similar to the VFT, fMRI studies have found that the Stroop task engages the brain's frontoparietal network. Within the frontal lobe, the colour-word Stroop task has produced significant brain activity in areas including the anterior PFC (BA10) [33,34], the dorsolateral PFC (BA9, BA 46) [27,34,35], the ventrolateral PFC (BA44, BA45) [32,34,35], and the premotor area (BA6) [32,34]. While some studies observed lateralized activity within specific prefrontal regions [27,34,35], others did not [32,33]. Bilateral activation in the superior [27,33,34] and inferior [27,33,35] parietal lobule (BA7, BA 40) has also been detected. Although cortical activity induced by the Stroop task has been detected using prefrontal NIRS measurements [36–38], this task has not been considered in NIRS-BCI applications to date.

1.3.3. Distinguishing between working memory and attention

While working memory and attention share common neural resources, direct intra-subject comparisons using fMRI have found that they are indeed separable mechanisms [24,25,32,39]. Differences in hemodynamic responses to working memory and attention have been observed within the frontal and parietal brain regions. In comparison to attention, greater working-memory induced activation has been observed in the left PFC (BA44) [25,39], left inferior parietal cortex (BA40) [39], and right inferior parietal cortex (BA40) [25]. Meanwhile, higher levels of activation induced by attentional tasks, relative to those involving working memory, have been observed in the right dorsolateral PFC [32,39]. At variance