Validation of a consumer-grade functional Near-Infrared Spectroscopy device for measurement of frontal pole brain oxygenation – an interim report

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Abstract

Consumer-grade neurotechnology products have been available for a few decades. Most of these products are based on electroencephalography (EEG), a technology that is known to be sensitive to noise. An alternative is functional Near-infrared spectroscopy (fNIRS), a growing neuroimaging technology, capable of measuring hemodynamic brain activity in real time. FNIRS has been validated successfully against functional magnetic resonance imaging (fMRI). Recently a miniaturized wireless consumer-grade fNIRS was introduced by the Swedish company Mendi. The present study aimed to compare measurements of brain activity from the Mendi fNIRS with an established laboratory fNIRS device. Nineteen participants (aged 18-53 years) performed two Stroop tests while frontal pole (Brodmann area 10) oxygenation was measured. First, in a laboratory setting with an fNIRS device from Biopac, and a few weeks later, the test was repeated in a home environment with the Mendi device. A preliminary analysis of the data showed a good agreement between the measurements for the two devices. At the group level, the correlation was 0.81. These interim results need to be corroborated by more robust analyses and follow-up studies but it is promising that the Mendi device provides valid measurements of brain activity at the group level and that the device may well be used for studies outside the laboratory.

Introduction

The interest in neurotechnology products for the consumer market is growing steadily. Many attractive applications for brain activity measurements outside the laboratory have been suggested, including for instance neurofeedback training, brain-computer interfaces, gaming, mediation practice, attention and impulse control training, self-monitoring in cognition tasks, or emotion self-regulation training (Balconi et al., 2018). Consumer-grade neurotechnology devices have been available for a few decades. EEG devices that dominate the market were first introduced in 2007. However, the spatial resolution of EEG is relatively low, and it is highly susceptible to electromagnetic noise and movement artifacts (Wexler & Thibault, 2019). Thus the validity and reliability of measurements from consumer-grade EEG devices have been questioned (Ratti et al., 2017; Maskeliunas et al., 2016; Sawangjai et al., 2015). An alternative or complementary technology for consumer devices is functional near-infrared

spectroscopy (fNIRS). This technique has developed rapidly over the past five years and miniaturized, wearable and wireless devices are available today (Pinti et al., 2019).

FNIRS ultimately probes neuronal activity via cerebral oxygenation and blood volume changes. It measures cerebral hemodynamic responses by near-infrared light. The rationale behind the technology is that changes in cerebral oxygen consumption increase with synaptic activity in a linear manner (Sheth., et al 2004). FNIRS devices can deliver continuous real-time measurements of oxygenated hemoglobin (HbO), deoxygenated hemoglobin (HbR) and total blood volume. Most fNIRS devices are based on continuous wave technology, which allows only relative estimations of hemoglobin changes. Hence, data needs to be analyzed by contrasting results from different tasks or conditions in cognitive studies in a similar way as for fMRI studies. There is also an ongoing development of fNIRS based on frequency domain methods (FD-fNIRS) that can deliver absolute baseline data (ratio-level data) (Fantini & Sassaroli, 2020).

fNIRS has several advantages but also disadvantages compared to other neuroimaging technologies. Similar to EEG, fNIRS is inexpensive, safe, very easy to use, and miniaturized wireless devices provide high degrees of portability for in-field applications. One main advantage of fNIRS compared to EEG, however, is that the technology is not susceptible to electromagnetic noise and relatively insensitive to movement artifacts. This allows for more versatile applications (participants can move and speak during the measurements), and potentially a higher signal quality during measurements outside of the laboratory. Moreover, fNIRS has a higher spatial resolution (2-3 cm) but lower temporal resolution compared to EEG. The main drawback of fNIRS compared to fMRI is the relatively low spatial resolution and the fact that penetration depth is only a few centimeters. As a result, fNIRS measurements are limited to cortical brain tissue. Of interest, although fNIRS signals are correlated with fMRI signals, they have a lower signal-to-noise ratio compared to fMRI (Cui et al., 2011). This observation likely results from strong confounding factors such as extracerebral tissue, scalp, skull, etc. and effects of blood pressure variations that are present in the fNIRS signal. Therefore, best practice applications require accounting for these confounding factors applying careful selection of artifact control and specific signal processing methods (Pint et al., 2019). Laboratory grade fNIRS devices have been validated against functional magnetic resonance imaging (fMRI) with good results especially for hemodynamic activity in the prefrontal areas that are important for executive function, working memory, impulse control, emotion regulation and planning. (e.g., Cui et al., 2010; Moriguchi et al., 2017; Bonetti et al., 2019). For recent reviews on the use of fNIRS for studying brain functions see Pinti et al., (2018a), Quaresima et al., (2019) and Kim., et al (2017 and wearable devices see Pinti et al., (2018b).

A first consumer-grade miniaturized, wireless fNIRS neurofeedback device was introduced by the Swedish company Mendi innovations AB in 2020. This device provides high usage flexibility and allows real-time measurement of the activity in anterior parts of the prefrontal cortex (Brodmann area 10). As such it allows conducting neurofeedback training outside of the laboratory. These kinds of devices open up new ways of conducting neurofeedback but also other kinds of neuroscientific research (“citizen science”; Parsons et al., 2011) However, ensuring sufficient signal quality is a major concern that has been raised by the scientific community (Naufel & Klein, 2020). Therefore, there is the need for validation of this type of device against established fNIRS devices.

The present article summarises a comparison between fNIRS signals acquired with a wireless mobile fNIRS (Mendi innovations AB, Stockholm, Sweden) consumer-grade equipment and those obtained with stationary laboratory equipment (fNIR100, Biopac®) while running a standard cognitive test. We used a stroop color word test (CWT) since it is known to put high demands on prefrontal systems, especially the dorsolateral prefrontal cortex (Yennu et al., 2015). The length of the CWT was approximately 12 minutes, a duration which should induce a high level of mental effort for most people. For this analysis, we reasoned that a good agreement between the results from the Mendi equipment and established laboratory equipment would validate the Mendi device as a consumer product and useful tool for research in cognitive neuroscience in home environments. We note, however, that the study was not originally designed to compare the signals between these devices. We rather used existing data that was collected during an experiment in our laboratory and repeated the paradigm using the Mendi neurofeedback device in the same participants in their home environment. Therefore, we limited the present analysis to a group-level analysis and did not compare individual time series data. Further, for the presented analyses we limited time intervals to 30 seconds for all comparisons. In this interim report, we provide a preliminary analysis of the data.

Methods

Participants

The participants (13 women, 6 men, M*age* =26.2, age range: 19-53 years) were recruited via the social network of a graduate student at the department of psychology Stockholm university. All participants gave their written informed consent and were compensated with $20 for their participation.

Materials and Procedure

The stroop color word test was run with PsychoPy 3.0 software on a Dell Optiplex 7070 SFF computer with a Dell P2419 screen. The test consisted of 4x4 incongruent color-word combinations, with the colors red, yellow, green and blue. Each word was presented for until the participant responded and the interstimulus interval was one second. The 16 combinations were repeated 15 times, resulting in a total of 240 presentations, divided into two sessions of 120 words with a 60-sec pause in between sessions. The participants were instructed to respond as fast and as accurately as possible with color marked (arrow) keys on a Dell 3KRP0 keyboard. They were allowed ten training trials before starting the test. The presentations were self-paced and lasted until the participant responded. Depending on how fast the participant responded, the stroop test lasted approximately 11-12 minutes.

The experiment was divided into two parts, which took place on different days. The intervals between the two parts where M=59.4 SD=7.2 days. In the first part we registered blood oxygenation of the prefrontal brodmann area 10 (BA10) during the stroop task with a sample rate 2 Hz using a laboratory-grade functional near-infrared spectrometer fNIR100 (Biopac®) equipped with 16 optodes and acquisition software Cobi Studio® (Ayaz et al., 2012) see figure 1. In the second part, the same participants repeated the same stroop test while blood oxygenation was registered in BA10 using a wireless consumer-grade functional near-infrared spectrometer from Mendi (v3–prototype, see figure 1) equipped with three

optodes (two channels) using a sampling rate of 33 Hz and an acquisition software from Mendi.

The two fNIRS devices differ with regard to the number of optodes and their placements. The optodes of the Mendi equipment measure activity in the frontal poles (BA10), one for the left and one for the right hemisphere. The Biopac records activity for the dorsolateral prefrontal areas and for the frontal pole. Thus, for all comparisons between devices the four frontal pole channels 7-10 of the Biopac were used. The mean activity of the channels 7 and 8 was used as a measure for left frontal BA10 oxygenation, and the mean of channels 9 and 10 was used for right BA10 oxygenation (see figure 1).

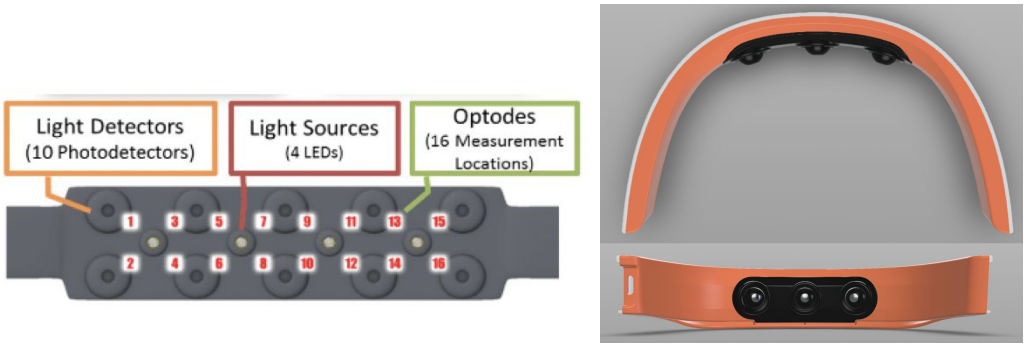

Figure 1. The 16 optodes for the Biopac device to the left (wires and hardware are not shown). The two optodes for the wireless Mendi device to the right.

Data analysis

Raw time-series data from the Biopac device were converted into changes in optical density and then into concentration changes by means of the modified beer lambert law using fNIR soft professional. Pre preprocessing was made according to Biopac recommendations with a hamming bandpass filter 0.01-0.2 Hz and a sliding window motion artifact rejection (SMAR) system (Ayaz et al., 2010). The raw data from the Mendi device was converted into changes in optical density and then into concentration changes by means of the modified beer lambert law. No additional filtering was applied. The time series of each participant were divided into 30-sec blocks (typically 23 blocks) and the average change in HbO was calculated for each block and compared for the two devices. Two of these blocks (12 and 13) represented the pause in-between sessions. Data were normalized to z-values at the individual level before calculating mean values across participants. Pearson and Spearman's correlations were calculated between the group averages of the two different devices.

Results

Here we present a preliminary analysis of the results. Figure 2 and 3 present group mean HbO data for the left and right frontal pole respectively during the stroop task. The mean results for the two devices show very similar oxygenation patterns during the whole stroop task with an exception for the pause-block 13, when data acquired with the Mendi device shows a lower level of oxygenation. During the first part of the stroop task both devices show a monotonically increasing oxygenation until a maximum is reached during block 10. At the

start of the second part of the experiment (block 14) both devices indicate that the oxygenation is markedly higher than at the start of the first part. Both devices indicate that the peak oxygenation is reached faster in the second part than in the first part.

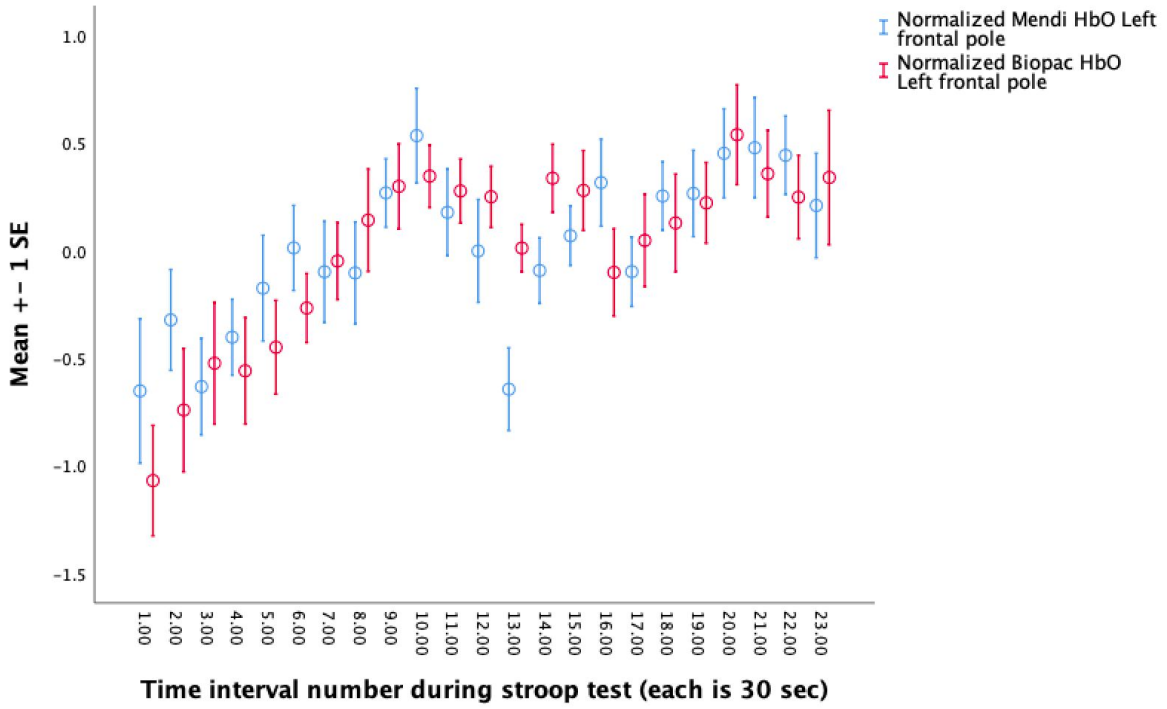

Figure 2. Mean (n=19) oxygenation of left BA10 a function of time divided into 30 sec intervals into the stroop task. Error bars represent the standard error of the mean. In intervals 12 and 13 there was a short pause between sessions.

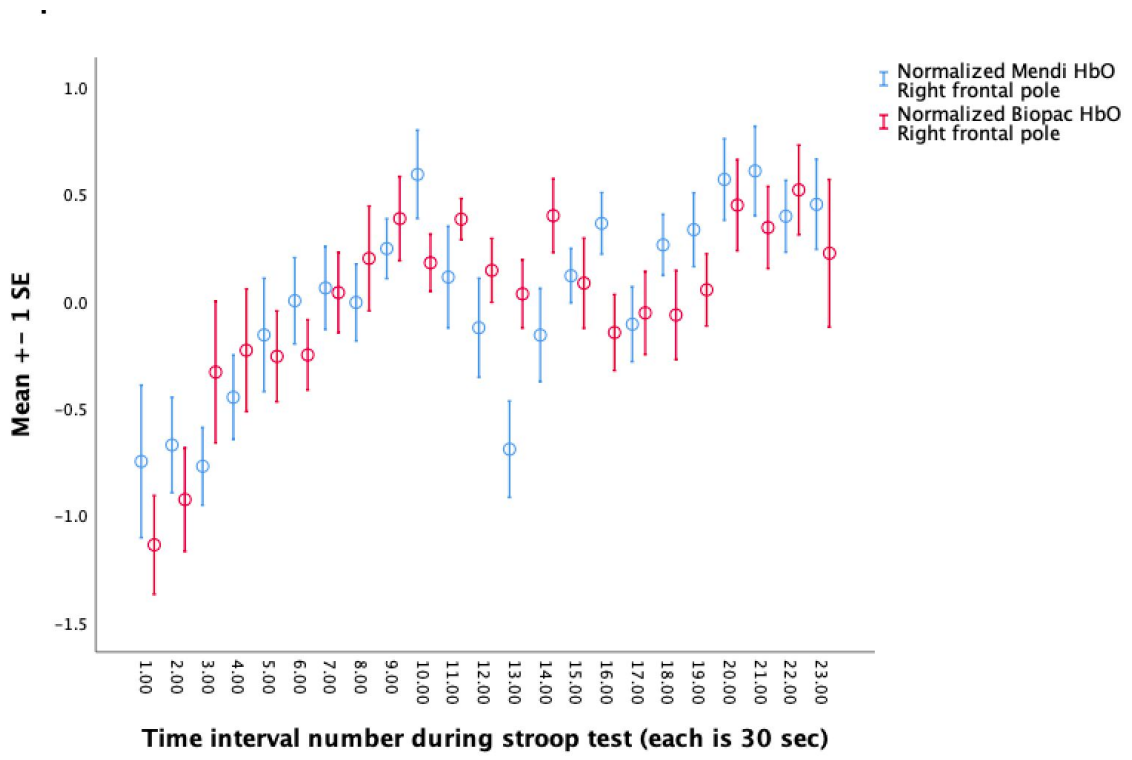

Figure 3. Mean (n=19) oxygenation of the right BA10 as a function of time divided into 30 sec intervals of the stroop task. Error bars represent the standard error of the mean. In interval 12 and 13 there was a short pause between sessions.

When excluding data from the pause (interval 12 and 13) the Pearson correlation coefficient between results for the Mendi and Biopac was r=0.81, n=21, p<0.001. When pause data was included, the correlation was r=0.74, n=23, p<0.001 p<0.001 (also the Spearman correlation was significant at p<0.001). The correlation between oxygenation of left and the right BA10 was r=0,964, n=21, p<0.001 for Mendi and r=0,933 n=21, p<0.001 for the Biopac equipment.

Discussion

Our preliminary analysis shows that there is a good agreement between data for the two devices at group level. Both devices show that the oxygenation of the left as well as right frontal pole increases almost monotonically as a function of time during the first part of the stroop test (before the 1 minute pause) and then plateaus (figures 2 and 3). The pattern is similar for the left and right hemisphere. At the pause (interval 12 and 13) the Mendi device shows a larger drop in oxygenation. This may be partly due to the fact that the participants were familiar with the experimental design when they took part for the second time.

Agreements were also observed for the second part of the experiment. Generally, the second part after the pause shows a somewhat different hemodynamic activity pattern as compared to the first part. The oxygenation level at the start of the second part was higher than for the first part. This observation is likely due to the lingering effect of the cognitive load experienced by participants during the first part of the experiment. Moreover, data from the end of the second part indicates a ceiling effect (time interval 20-23). This ceiling effect

likely results from participants reaching their oxygenation limits for BA10 at this time. We note that the stroop task is cognitively very demanding, especially when it is applied for longer periods (10 minutes).

Limitations and Outlook

Several limitations of this study deserve consideration. First, differences in anatomical coverage of the two devices may have resulted in signal differences. While we used 4 of the 16 channels of the Biopac system, the Mendi device has only two channels to measure oxygenation of the anterior PFC and hence both devices capture slightly different subparts of the anterior PFC. Despite these differences, we found agreements between the measurements at the group level. A future study design would benefit from electronically registering optodes within the same space to ensure that their positions relative to the subject's head are more comparable between devices.

Second, part of the data stems from a laboratory experiment designed for an ego-depletion study, which was later repeated in the same participants in their home environment. Contextual differences during the two measurements and differences in task timing (which was self-paced) did not allow us to compare signals on the individual level, but only compare means on the group level. Comparisons with regard to signal quality and reliability require an adequately designed study.

Third, we acknowledge that the present report serves merely as an interim summary to provide the community with a snapshot of our ongoing work. This also affects data preprocessing, e.g. different methods were used for the two devices, which may yield suboptimal results. For the future, we plan to conduct a more robust analysis using the same preprocessing methods for the data of both devices. Further, we will also analyze deoxygenation data to assess the robustness of these results.

Lastly, we note that the validity and reliability of measures of hemodynamic brain activity remains a topic for current debates within the neuroscience community. For instance, poor test-retest reliability has been reported recently for task-based fMRI measurements. (Elliot, et al 2020). It will thus be important for future experiments to focus on both the validity and reliability of measurements at the individual level. We intend to achieve this by tailoring task designs and conducting measurements in the same settings during the same day or even conduct simultaneous measurements if possible. Further, we intend to collect larger sample sizes and preferably make use of repeated measure study designs that allow assessing retest reliability over a longer period.

Conclusion

Despite these limitations the present interim report suggests that the portable Mendi fNIRS device produces valid measurements of hemodynamic brain activity at group level if compared to a lab-grade fNIRS device. If these initial results will be corroborated by additional studies including a more robust analysis, the equipment may be useful for both consumer applications as well as for research in cognitive neuroscience outside the laboratory.

Conflict of interest

This study was partly funded by Mendi innovations AB, Stockholm, Sweden and Lennart Högman AB, Stockholm, Sweden. LH received a one-off payment for conducting this study by Mendi innovations AB, Stockholm, Sweden.

Data availability statement

We plan to make the data openly available in the future. For now, data will be made available upon reasonable request.

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