Comparison of a Custom Functional Near-infrared Spectroscopy Sensor, a Peripheral SpO2 Sensor, and a Standard Laboratory Sensor (Biopac) for RR-Interval Assessment

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Abstract: Across many careers, individuals face alternating periods of high and low cognitive workload which can impair cognitive function and undermine job performance. We have designed and are developing an unobtrusive system to Monitor, Extract, and Decode Indicators of Cognitive Workload (MEDIC) in real-world environments. With our partners at Biosignals Plux, we designed and manufactured a functional near-infrared spectroscopy (fNIRS) device that measures brain blood oxygenation and cardiac information in a form-factor that can be mounted on the inside of a baseball cap or headband. Because MEDIC is designed to be used in realistic, sometimes high-motion environments, changes in blood oxygenation to the brain must be put in context of current levels of physical activity without intruding on the activity of the user. Therefore, we also developed a NIRS Armband device made up of a combination of Plux sensors including: SpO2 sensor to measure cardiac information, a galvanic skin response sensor, a 6-axis accelerometer, and a non-contact skin temperature sensor. Because these were custom sensors, we tested them against a standard laboratory sensor (a Biopac RSPEC-R) while participants completed an obstacle course of cognitive and physical tasks.

1 INTRODUCTION

Across many careers, individuals face alternating periods of high and low cognitive workload which can impair cognitive function and undermine job performance. We have designed and are developing an unobtrusive system to Monitor, Extract, and Decode Indicators of Cognitive Workload (MEDIC) in real-world environments. With our partners at Biosignals Plux, we designed and manufactured a functional near-infrared spectroscopy (fNIRS) device in a form-factor that can be mounted on the inside of a baseball cap or headband. fNIRS is useful to detect blood oxygenation changes associated with cognitive states of interest, such as cognitive workload (Tichauer, Hadway, Lee et al., 2005; Keller, Nadler, Alkadhi et al., 2003). When cognitive workload increases, there is a corresponding increase in prefrontal blood oxygenation until the task becomes too difficult, at which point blood oxygenation decreases (Bunce, Izzetoglu, Ayaz et al., 2011; Ayaz, Cakir, Izzetoglu et al., 2012; Ayaz, Shewokis, Bunce et al., 2012). Because MEDIC is designed to be used in realistic, sometimes high-motion environments, changes in blood oxygenation to the brain must be put in context of current levels of physical activity without intruding on the activity of the user. Therefore, we also developed a near infrared spectroscopy (NIRS) Armband device that includes a SpO2 sensor to measure cardiac information, a galvanic skin response sensor, a 6-axis accelerometer, and a non-contact skin temperature sensor. Because these were custom sensors, we tested them against a standard laboratory sensor – a Biopac RSPEC-R– while participants completed an obstacle course of cognitive and physical tasks.

2 METHODS

We first designed a forehead sensor device that includes a custom fNIRS sensor and a three-axis accelerometer designed to be integrated into a baseball cap or headband, or standard issue gear such

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as a helmet or surgeon's cap. This sensor is more portable and less obtrusive than most commercially-available sensors. alone (top left), mounted inside a helmet (top right), being worn during a jump roping task (bottom left), and being worn during a medical training simulation (bottom right).

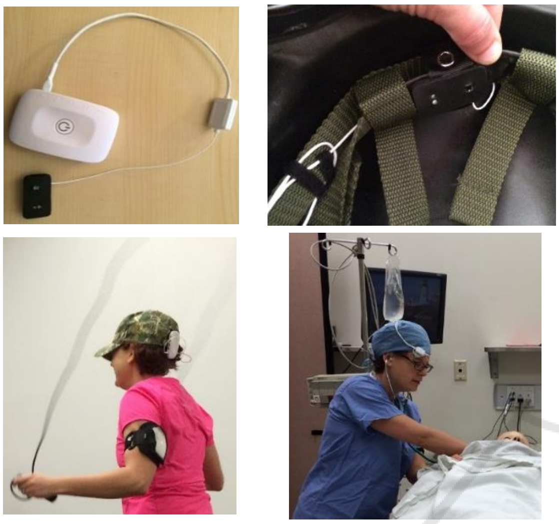

Figure 1: Custom fNIRS sensor alone (top left), mounted inside a helmet (top right), worn during jump roping (bottom left), and worn during a medical training simulation (bottom right).

Participants wore Charles River Analytics/Plux sensors and standard sensors (Biopac) while completing well-validated cognitive tasks, physical tasks, and combinations of cognitive and physical tasks. This allowed us to assess the accuracy of Charles River Analytics/Plux sensors (by comparing them to Biopac data).

The evaluation of this sensor suite included 21 teams of three undergraduates completing physical and cognitive challenges. (1) Baseline involved sitting quietly. (2) Word list memorization (Miller, 1956) required participants to remember as many words as possible. (3) Balance board required participants to coordinate rolling a ball edge to edge on a large, flat, weighted board without dropping it for a specified amount of time. (4) For twenty questions (Denney, 1987), participants asked yes-or-no questions (up to 20) of the experimenter to identify a pre-specified object. (5) For the puzzle task (Shepard & Metzler, 1971; Guastello et al., 2014), participants put together standard cardboard or plastic puzzles of varying difficulty. (6) For hot potato, participants each maintained balance on a BOSU ball while passing weighted (medicine) balls from one individual to the next. (7) For logic problems (Braine, 1990), individuals were given logic puzzles to solve (e.g., http://www.brainbashers.com/logic.asp). (8) For moving boxes (Amazeen, 2013), participants lifted and moved boxes of variable weights and sizes to construct a wall. (9) For jump rope, participants jumped synchronously to complete a specified number of consecutive jumps.

3 RESULTS

Sixty-three participants were recruited from Arizona State University (ASU) and surrounding areas in Mesa to participate in a study examining team coordination. Informed consent was obtained prior to the start of the experimental session. Each participant received $20 upon completion of the experimental session. The experimental protocol was approved by ASUs Institutional Review Board and participants were treated in accordance with the ethical guidelines of the American Psychological Association.

Participants were grouped into three-member teams, for a total of 21 teams. Data from seven teams were removed from analysis due to logistical (e.g., incomplete teams) and technical (e.g., equipment failure) difficulties. The following results comprise data from the remaining 14 teams (see Table 1).

Table 1: Sample demographics. Mean (standard deviation).

Team	Male/ Female	Age (years)	Weekly Exercise (hours)
3	1/2	26.7 (5.5)	4.7 (2.5)
4	3/0	24.0 (1.7)	5.7 (1.5)
5	2/1	23.3 (0.6)	5.3 (2.3)
6	2/1	24.3 (2.9)	4.2 (1.4)
7	3/0	21.7 (2.5)	6.0 (5.3)
9	3/0	24.3 (0.6)	6.7 (2.1)
10	2/1	27.7 (6.4)	9.0 (9.6)
12	3/0	23.7 (0.6)	5.3 (1.5)
13	3/0	23.7 (1.2)	1.3 (1.5)
14	2/1	25.3 (2.1)	7.7 (2.1)
17	2/1	22.3 (0.6)	8.3 (5.1)
18	2/1	25.3 (0.6)	4.8 (2.0)
19	3/0	26.3 (0.6)	4.7 (2.5)
21	2/1	22.3 (0.6)	8.8 (5.4)

Various physiological measures were collected from each participant. Plux sensors were positioned on the non-dominant arm (i.e., Armband) and forehead (i.e., fNIRS Device) of each of the three participants. A Biopac wireless ECG transmitter (Biopac Systems Inc., Goleta, California, USA) was used to collect electrocardiogram (ECG) data from two of the three participants. Output from the Biopac transmitter was transmitting in real time to a PC and recorded at 1000 Hz using AcqKnowledge software (Biopac Systems Inc.). ECG signals were filtered and down-sampled to 250 Hz for later calculation of RR interval, the time (sec) between two consecutive QRS complexes, using MATLAB (Mathworks, Inc.).

The experimental session consisted of one four-minute baseline and nine two-minute cognitive and physical tasks. Teams completed the baseline once, at the beginning of the experimental session. They then completed two repetitions of the coordination task sequence. Experimental sessions lasted approximately 75 minutes.

3.1 Signal Comparison

Figure 1, Figure 2, and Figure 3 depict the RR interval time series from the Charles River Analytics/Plux fNIRS device (red line) and Biopac transmitter (blue line) for one participant over the entire experimental session. Time series' were smoothed using a 10- (Figure 1), 20- (Figure 2), and 30-point (Figure 3) moving average. Across all figures, the measured heart beat was similar for both devices. Fluctuations in RR interval can be seen as the participant's heart rate oscillates between physical (smaller RR interval/higher heart rate) and non-physical tasks (larger RR interval/lower heart rate). To determine the relationship between the two time series (Charles River Analytics/Plux fNIRS, Biopac), we computed the cross-correlation (r) using the "crosscorr" function in MATLAB. Correlations are depicted in the bottom left region of each figure. Examination of those correlations reveals stronger relationships between the data sets for the 30 second window size. This trend is also observed in Table 2. This suggests that a 30 second window is sufficient to preserve and enhance the dominant (slower) frequencies of the participant's RR interval_signal during physical and non-physical tasks.

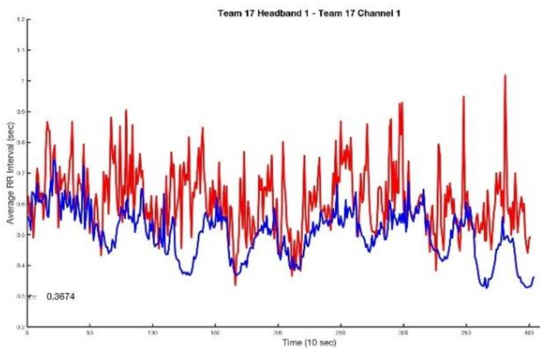

Figure 1: Charles River Analytics/Plux fNIRS device (red) and Biopac (blue) RR interval averaged across 10s windows.

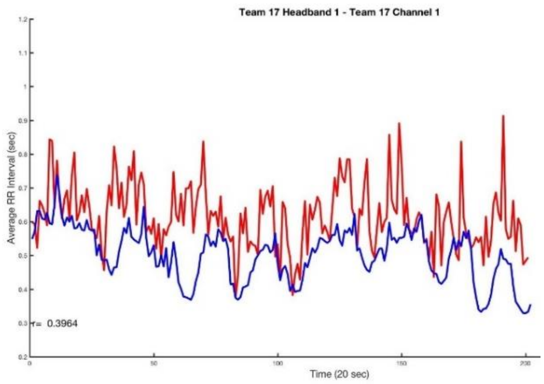

Figure 2: Charles River Analytics/Plux fNIRS device (red) and Biopac (blue) RR interval averaged across 20s windows.

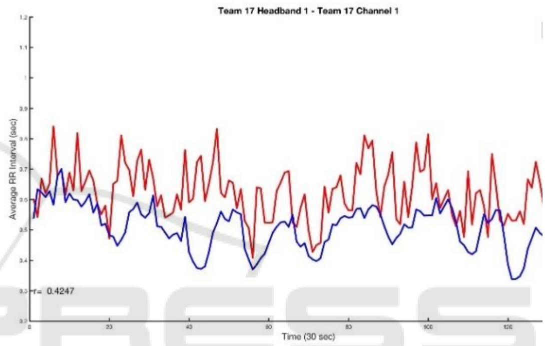

Figure 3: Charles River Analytics/Plux fNIRS device (red) and Biopac (blue) RR interval averaged across 30s windows.

Note that the correlations in Table 2 are small but positive, indicating that the sensors are picking up on similar information, but there is weak correspondence.

Table 2: Cross-correlation (mean ± standard deviation) for each window size.

Window Size (sec)	Armband–Biopac	fNIRS Device – Biopac
10	0.188 ± 0.180	0.211 ± 0.196
20	0.206 ± 0.189	0.230 ± 0.211
30	0.228 ± 0.195	0.249 ± 0.227

Figure 4, Figure 5, and Figure 6 depict RR interval data from the Armband (red line) and corresponding Biopac transmitter (blue line) from the same participant in Figure 1, Figure 2, and Figure 3. For all figures, we constrained the RR interval scale from 0 to 4 so that fluctuations in the Biopac signal could still be seen. However, it should be noted that RR intervals sometimes extended well past 4, meaning that the time between heart beats was 4 seconds. This is obviously unrealistic. This artifact existed across three types of signals (Armband, fNIRS Device, Biopac sensor) but was most problematic with Armband data, as can be seen in lower correlations for Armband and Biopac data than fNIRS Device and Biopac data in Table 2.

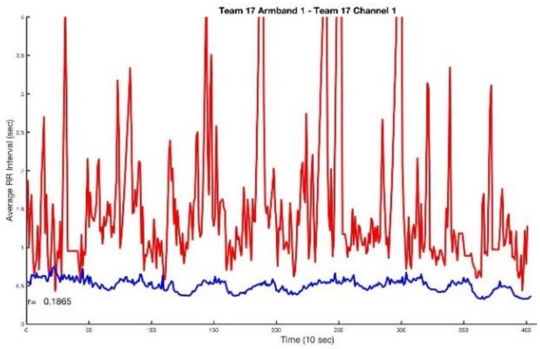

Figure 4: Plux Armband and Biopac RR interval averaged across 10 second windows.

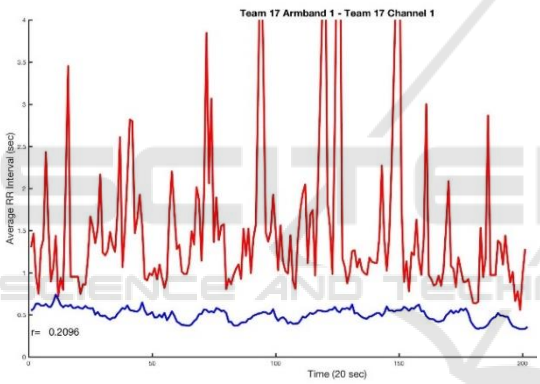

Figure 5: Plux Armband and Biopac RR interval averaged across 20 second windows.

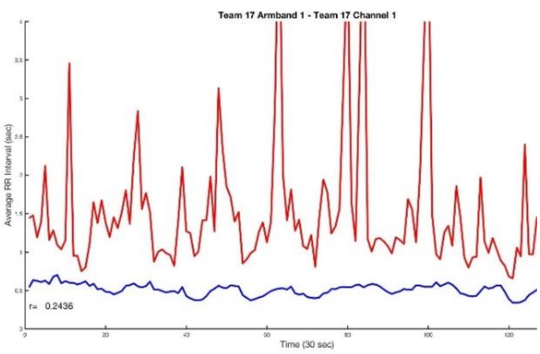

Figure 6: Plux Armband and Biopac RR interval averaged across 30 second windows.

3.2 Task Evaluation

To determine whether the tasks had an effect on heart rate behaviour, we examined the average RR interval during the performance of each task in Trials 1 and 2 separately. Figure 7 and Figure 8 depict the RR intervals from Biopac for two participants in Teams 18 as a function of the task. As expected, participants exhibited an increase in heart rate (indicated by a lower RR interval) for the physically demanding tasks (e.g., moving boxes) compared to the cognitive tasks (e.g., puzzle). Because the sequence of the tasks alternated between cognitive and physical tasks, we can see the heart rate oscillate as a function of the task demands. The same pattern was observed during trial 2, along with lower overall RR interval values (i.e., higher heart rate). Even though participants were given time to rest in between trials, heart rate never fully returned to Baseline.

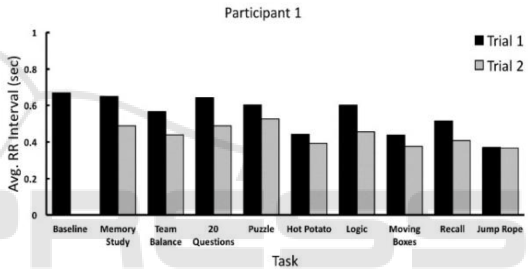

Figure 7: Mean RR interval as a function of task in (black bars) trial 1 and (grey bars) trial 2.

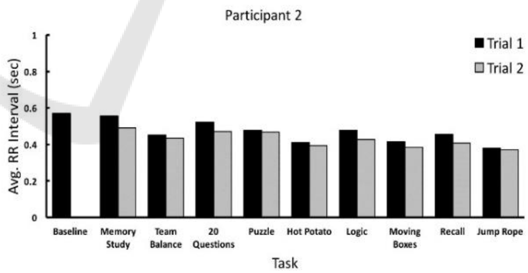

Figure 8: Mean RR interval as a function of task in (black bars) trial 1 and (grey bars) trial 2.

The same pattern was observed across all teams, as seen in the group averages of Figure 3.

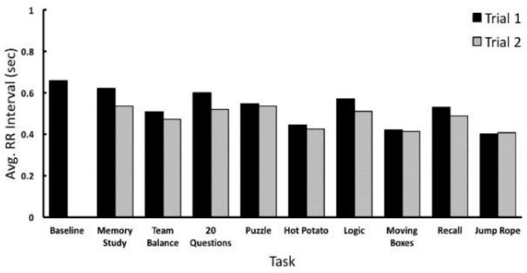

Figure 9: Mean RR interval as a function of task in (black bars) trial 1 and (grey bars) trial 2 across all teams.

4 CONCLUSIONS

Participants wore Charles River Analytics/Plux sensors and standard sensors (Biopac) while completing well-validated cognitive tasks, physical tasks, and combinations of cognitive and physical tasks. This allowed us to assess the accuracy of Charles River Analytics/Plux sensors (by comparing them to Biopac data). The evaluation of this sensor suite included 21 teams of three students completing physical and cognitive challenges. Various physiological measures were collected from each participant.

The correlations in RR interval between the fNIRS device, Armband device, and Biopac sensor are small, but positive, indicating that the sensors are picking up on similar information, but there is weak correspondence.

The physical and cognitive tasks had very different effects on heart rate. As expected, the ECG signal was much more variable during the completion of the physical tasks, including movement between stations of the experiment. Occasionally, a sensor might be sufficiently jostled, particularly in the rope jumping task, or it might fall off. In those situations, the signal became very noisy, which made the QRS complex difficult to resolve. The consequence was that the peak-picking algorithm might skip relevant peaks in the signal and estimate an inflated RR interval (e.g. RR interval>2 sec).

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