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EEG from a single-channel dry-sensor recording device

Stuart J. Johnstone

University of Wollongong, sjohnsto@uow.edu.au

R Blackman

University of Wollongong, russellb@uow.edu.au

Jason Bruggemann

University of Wollongong, jmb02@uow.edu.au

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EEG from a single-channel dry-sensor recording device

Abstract

While a laboratory setting and research-grade electroencephalogram (EEG) equipment allow control of variables and high-quality multiple-channel EEG recording, there are situations and populations for which this is not suitable. The present studies examined the validity of a new method of single-channel EEG measurement that is portable and uses dry-sensor technology. In study 1, EEG was recorded simultaneously from the portable device and 4 standard EEG electrodes from a research system, during eyes open (EO) and eyes closed (EC) resting conditions, with 20 adult participants. Average correlations with the research system frequency spectra were highest at site F3 for portable device data processed onboard of the device ($r = .90$), and for device data processed in a standard manner ($r = .89$). Further, predictable variations in EO versus EC comparisons were observed. In study 2, twenty-three healthy children had EEGs recorded from the portable device during EO and EC resting conditions, and 3 EO active conditions (ie, relaxation, attention, and cognitive load). Absolute and relative EEG band power differed between conditions in predicted ways, including a reduction in relative theta power and an increase in relative alpha power in EC compared to EO resting conditions. Overall, the results suggest that, while limited in terms of scalp recording locations, the portable device has potential utility in certain EEG recording situations where ease of use is a priority.

Keywords

sensor, device, dry, recording, channel, single, eeg

Disciplines

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Title

EEG from a single channel dry sensor recording device

Authors

Dr. Stuart J. Johnstone

Brain & Behaviour Research Institute, School of Psychology, University of Wollongong, Wollongong NSW
2522 AUSTRALIA.

Mr. Russell Blackman

Brain & Behaviour Research Institute, School of Psychology, University of Wollongong, Wollongong NSW
2522 AUSTRALIA.

Dr. Jason Bruggemann

School of Psychiatry, University of New South Wales and Neuroscience Research Australia, Randwick,
NSW 2031 AUSTRALIA

Corresponding author

Dr. Stuart Johnstone, School of Psychology, University of Wollongong, Wollongong NSW, 2522. Phone:
+61 2 4221 4495. Fax: +61 2 4221 4163. E-mail: sjohnsto@uow.edu.au

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ABSTRACT

While a laboratory setting and research-grade EEG equipment allow control of variables and high quality multiple-channel EEG recording, there are situations and populations for which this is not suitable. The present studies examined the validity of a new method of single-channel EEG measurement that is portable and uses dry sensor technology. In Study 1, EEG was recorded simultaneously from the portable device and 4 standard EEG electrodes from a research system, during eyes-open and eyes-closed resting conditions, with 20 adult participants. Average correlations with the research system frequency spectra were highest at site F3 for portable device data processed on-board the device ($r = 0.90$), and for device data processed in a standard manner ($r = 0.89$). Further, predictable variations in eyes-open versus eyes-closed comparisons were observed. In Study 2, 23 healthy children had EEG recorded from the portable device during eyes-open and eyes-closed resting conditions, and 3 eyes-open active conditions (i.e. Relaxation, Attention and Cognitive Load). Absolute and relative EEG band power differed between conditions in predicted ways, including a reduction in relative theta power and an increase in relative alpha power in eyes-closed compared to eyes-open resting conditions. Overall the results suggest that, while limited in terms of scalp recording locations, the portable device has potential utility in certain EEG recording situations where ease-of-use is a priority.

Keywords

EEG, portable, dry sensor, validation, children, adults

INTRODUCTION

Measurement of brain electrical activity via an electroencephalograph (EEG) typically occurs in a laboratory, a setting which allows careful and necessary control of variables. In the laboratory, participants typically have numerous recording electrodes fitted to the head and other parts of the body, including the fingers and chest. Participants often report discomfort during the lengthy setup procedure and also during the experimental session, making concentration difficult during completion of the required experimental tasks. These electrodes are attached to recording equipment (e.g., signal amplifier), which places further restrictions on the participant in terms of movement and comfort, and limits the range of possible recording situations and locations. In addition to these general limitations, lab-based recording can be extremely difficult for certain populations. For instance, young children who are cognitively impaired, clinically anxious, or mobility restricted. There are also situations when very frequent recordings are required, such as in medication monitoring or neurofeedback training applications.

In recent years there have been several wireless EEG devices released, with the number of recording channels ranging from one up to fourteen. These devices represent impressive attempts to address the issues outlined above and move towards EEG recording systems that are easy to fit and use, portable and wireless^[1], in order to facilitate use at home and during daily activities. They are increasingly referred to as “brain-computer interface” devices, providing a pathway for communication between the brain and an external device, with possible uses ranging from gaming and entertainment to traditional research. In the gaming domain, change in the EEG signal can be harnessed as a control mechanism during game play (e.g., if relative beta activity exceeds a threshold then a closed door will open). In the research domain, such devices may be applicable in situations that do not require topographic definition but rather demand ease-of-use or the capacity for frequent recordings; for example EEG studies involving children with intellectual disabilities who typically have a low tolerance for traditional EEG setup procedures. Despite the great potential of brain-computer interface devices for research, these devices have yet to be validated for scientific use.

The current paper examines the validity of a new method of single-channel EEG measurement that is portable, uses dry-sensor technology and transfers data wirelessly. The portable device, referred to as a headset here, is worn like a set of headphones and takes less than 20 seconds to fit. The headset measures EEG from one anterior frontal scalp location (AF3) at 128 Hz, and calculates and outputs EEG band power data at 2 Hz. To be useful as a tool for research/monitoring, the raw EEG from the headset must show concurrent validity with EEG simultaneously recorded from a research system, as well as predictable sensitivity to variations in psychological state.

One case study report has shown that EEG power spectrum data obtained using a headset system shows sensitivity to variations in psychological state, such as higher proportions of relative beta activity during cognitively demanding periods (e.g. in class) compared to between-class breaks, and an increasing proportion of delta activity during stage 1 to 4 sleep cycles ^[2]. While providing face validity, further validation work with many more subjects under controlled conditions is needed.

In this paper we tested the validity of a headset system using EEG power spectrum. This was done in 2 studies. In Study 1 we tested the concurrent validity of the headset system in adults by correlating measures of the EEG spectrum that were simultaneously recorded with headset and research EEG electrodes. In Study 2 we tested the comparative validity of the headset system in children by comparing the EEG power spectrum measured in eyes-open and eyes-closed resting conditions, and in three active conditions (relaxation, attention, cognitive load). If the headset system had good comparative validity, the results would show that frontal relative alpha power will be increased in eyes-closed compared to eyes-open resting conditions, and that decreases in delta and increases in beta would occur in conditions with high cognitive demand ^[3, 4].

MATERIALS AND METHODS: STUDY 1

Participants

Twenty adults (6 female) with no known psychological or physical health problems, who were free of caffeine for 24 hours prior to recording, participated in Study 1. The research protocol was approved by the joint Illawarra Area Health Service/University of Wollongong Human Research Ethics Committee prior to commencement.

Equipment

The headset records EEG using dry sensor technology, which consists of a microchip and embedded firmware, and 10 mm active, material reference and ground electrodes (termed ThinkGear; NeuroSky, USA) contained within a comfortable set of headphones (termed Mindset; NeuroSky, USA) as shown in Figure 1. Electrical potentials at the active and reference electrodes are subtracted through common mode rejection to derive a single EEG channel signal which is amplified 8000 times. The signals are band-pass filtered (1-40 Hz) and sampled at 128 Hz. Proprietary algorithms detect and correct eye movement and muscle artefacts in the time domain, prior to Fourier transformation of each 0.5 second epoch in 0.25 Hz bands. It is possible that the artefact rejection methods are not 100% efficient and residual artefacts could be present in the data.

A research-grade EEG recording system (Nuamps, Neuroscan, USA) was used to record EEG at 500 Hz from electrode positions F3, FP1, F7 and EOG (referenced to nose tip; band-pass 1-50 Hz) while EEG at 128 Hz was simultaneously recorded from position AF3 of the 10-10 system (referenced to left ear; band-pass 1-50 Hz) using the headset. The research system scalp sites were chosen due to their proximity to the headset electrode, with the EOG used as a non-scalp comparison, and to facilitate simultaneous fitting of the required reference electrodes and headset. As in previous parallel evaluations, an exact match between the recording parameters of the two systems was neither expected nor possible due to the presence of various hardware features such as filters with differing filter responses capabilities^[1].

-- Insert Figure 1 about here --

Procedure

Participants were required to sit quietly with their eyes closed, and sit quietly with their eyes open, each for 2 minutes while EEG was recorded, with the order of task counterbalanced between participants. After the recording session, Scan Edit software (Neuroscan, USA) was used to re-sample the research system EEG from 500 Hz to 128 Hz; calculate FFTs (10% Welch window) for each artefact-free 4.0 second EEG epoch (1/4 Hz resolution) for the research system and headset data; band-pass filter at 2-30 Hz; and average the FFTs, resulting in the across subject means shown in Figure 2. Power spectrum data were also obtained from headset log files written to the recording computer. The power spectrum data were summed offline to derive power in four frequency bands (Delta: 2.0-3.5 Hz; Theta: 3.75-7.5 Hz; Alpha: 7.75-12.5 Hz; Beta: 12.75-25 Hz). Relative power was calculated by first summing power across the delta, theta, alpha and beta bands to compute total power, and then dividing the power for each individual band by the total power, expressed as a percentage.

RESULTS: STUDY 1

The mean age of participants was 24.3 years (SD 7.7 years). Averaged power spectra for the EO and EC resting conditions are shown in Figure 2, for the headset EEG processed in Scan (HS), headset EEG processed on-board (HS-OB) and at the four research system EEG channels processed in Scan. To examine the relationship between the two headset-derived spectra and each research system EEG site, correlations were determined across the 0-30 Hz range for each pairing for each participant separately, with means shown in Figure 3.

-- Insert Figures 2 and 3 about here --

The correlation coefficients were subject to repeated measures ANOVA with Site (F3, FP1, F7, EOG), Condition (EO, EC) and Headset-measure (Scan-derived, HS-derived) as within subjects factors. A Site

main effect and planned contrasts indicated that the correlation coefficient was significantly higher at F3 (0.87) than FP1 (0.79; $F[1,19]=28.8$, $p<.001$), F7 (0.82; $F[1,19]=35.6$, $p<.001$) and EOG (0.58; $F[1,19]=85.5$, $p<.001$). A main effect of Headset-measure indicated that the correlations with research system data were higher for HS-derived than Scan-derived spectra (0.79 vs. 0.74; $F[1,19]=16.2$, $p<.01$). There was no significant main effect of Condition, or interactions with Condition or Headset-measure.

Next, relative band power was calculated for the EO and EC resting conditions for the four research system sites (F3, FP1, F7, EOG) as well as the headset data processed in Scan (i.e. HS) and headset data processed on-board the headset (i.e. HS-OB). A repeated measures ANOVA with Site (F3, FP1, F7, EOG, HS, HS-OB) and Condition (EO, EC) as within subjects factors was carried out for delta, theta, alpha and beta relative band power separately. This allowed examination of relative power differences between Sites, and importantly a comparison of the EO versus EC differences between Sites. Given that site F3 showed the strongest correlations between HS (and HS-OB) and research system frequency spectra, planned contrasts compared each other level to F3. Figure 4 shows data as well an effect summary.

-- Insert Figure 4 about here --

A main effect of Site and planned contrasts revealed that, compared to F3, relative delta power did not differ for HS-OB, was reduced for the HS ($F[1,18]=45.7$, $p<.001$), and was increased at FP1 ($F[1,18]=52.1$, $p<.001$), F7 ($F[1,18]=17.9$, $p<.001$) and EOG ($F[1,18]=31.6$, $p<.001$). The Site x Condition interaction and planned contrasts revealed that the F3 EO vs. EC difference (i.e. reduced in EC) was not significantly different for HS and HS-OB, was reduced at F7 ($F[1,18]=7.3$, $p<.05$) but was reversed for FP1 ($F[1,18]=7.9$, $p<.05$) and EOG ($F[1,18]=12.3$, $p<.05$).

Compared to F3, relative theta power did not differ for HS, was increased for HS-OB ($F[1,18]=11.0$, $p<.01$) and was reduced at FP1 ($F[1,18]=21.1$, $p<.001$), F7 ($F[1,18]=26.7$, $p<.001$) and EOG ($F[1,18]=28.8$, $p<.001$)

across Conditions. The F3 EO vs. EC difference (i.e. slightly reduced in EC) was larger for HS ($F[1,18]=16.6, p<.01$) and HS-OB ($F[1,18]=9.3, p<.01$) but was opposite (i.e. larger in EC) at FP1 ($F[1,18]=35.5, p<.001$), F7 ($F[1,18]=9.7, p<.01$) and EOG ($F[1,18]=8.3, p<.01$).

Relative alpha power did not differ at F7, but was increased for HS ($F[1,18]=83.1, p<.001$) and HS-OB ($F[1,18]=59.9, p<.001$) and reduced at FP1 ($F[1,18]=22.7, p<.001$) and EOG ($F[1,18]=56.1, p<.001$) compared to F3 across Conditions. The F3 EO vs. EC difference (i.e. increased in EC) did not differ at HS, FP1, F7 or EOG, and was increased for HS-OB ($F[1,18]=4.8, p<.05$).

Compared to F3, relative beta power did not differ for HS and FP1, was reduced for HS-OB ($F[1,18]=251.8, p<.001$) and increased for F7 ($F[1,18]=8.0, p<.05$) and EOG ($F[1,18]=26.4, p<.001$) across Conditions. The F3 EO vs. EC difference (i.e. slightly reduced in EC) did not differ for HS-OB, FP1 and F7, was larger for HS ($F[1,18]=5.4, p<.05$), but was opposite at the EOG site ($F[1,18]=25.9, p<.001$).

In summary, the results of the ANOVA and contrasts indicate that while there were some differences in the magnitude of relative band power between the HS, HS-OB and scalp sites, the EO versus EC differences at F3 were in the same direction for the HS and HS-OB in all cases.

DISCUSSION: STUDY 1

In this study the parallel evaluation method was adopted to compare simultaneously recorded data from the headset and proximal electrodes connected to a research system with adult participants. It should be noted that 100% correspondence between the headset-derived and research system data was not expected due to the differences in recording parameters and scalp locations.

Strong positive relationships were evident between the frequency spectra of simultaneously recorded headset and research system EEG that were both subsequently processed using the same analysis procedure in Scan,

providing some evidence for the validity of the raw 128 Hz EEG waveform from the headset. These results suggest that the raw EEG data recorded by the headset with a dry-sensor system is of adequate quality.

The crucial relationship in terms of concurrent validity was between the frequency spectra of headset EEG processed on-board (i.e. HS-OB) and the corresponding spectra of Neuroscan EEG processed in Scan. The strong positive relationships found here indicate the validity of the FFT processing of raw EEG data carried out on-board the headset. These results suggest that the raw EEG waveform recorded by the headset is very similar to research system EEG in terms of its underlying frequency characteristics, and further that the FFT calculations carried out on board the headset (and then sent via Bluetooth to the recording PC) are very similar to research system EEG analysis.

The relative band power analyses revealed some differences in the headset measured band power compared to the research system acquired at F3, across EO and EC conditions. For headset data processed in Scan there was reduced power in the delta band and increased power in the alpha band. For headset data processed on-board there was increased relative power for theta and alpha as well as reduced power for beta. While this may initially appear an issue for the headset data, it is important to note the similar lack of consistency between F3 and the other research system sites (e.g. delta power larger at FP1 and F7 than F3; theta power smaller at FP1 and F7 compared to F3).

The pattern of EO versus EC differences observed for the research system data at F3 were similar to those observed for the headset and headset-OB data. Importantly, there were no cases in which the direction of the EO versus EC difference was opposite to F3, as was the case at some other research system sites (e.g., delta at FP1/EOG; theta at FP1/F7/EOG; beta at EOG).

In summary, the results of Study 1 provide evidence for the concurrent validity of the raw 128 Hz EEG waveform from the headset, and the FFT processing of that raw EEG data carried out on-board the headset.

Further, analyses of relative band power provided evidence of similar sensitivity to psychological state variations for the concurrently recorded headset and research system EEG.

MATERIALS AND METHODS: STUDY 2

Participants

Twenty three healthy children (6 females) aged from 7 to 14 years participated in this study. These participants were recruited from the Illawarra and southern Sydney area via advertisements, and reported no significant vision or hearing problems. Exclusion criteria included an estimated IQ of <80, a clinically significant psychological disorder or learning disability, periods of unconsciousness, a history of seizures or epilepsy. Informed written consent was obtained from the parent and child after careful explanation of procedural requirements. The data presented here represent a small part of the overall research protocol, which was approved by the joint Illawarra Area Health Service/University of Wollongong Human Research Ethics Committee prior to commencement.

Equipment

Behavioural ratings were collected from parents using the Conners' Parent Rating Scale - Revised (CPRS-R)^[5] to characterise the child's typical behaviour in the preceding week. A two subtest version of Wechsler's Abbreviated Scale of Intelligence (WASI) was used to estimate each participants IQ, and spelling ability was examined with the South Australian Spelling Test (SAST)^[6].

Procedure

After an expression of interest in the study, the parents of participants were sent a comprehensive information pack detailing procedures. Following verbal agreement to participate a recording session was scheduled at the participant's home or at the university. Two researchers attended each recording session, and informed written and verbal consent was obtained from both the parent(s) and child. The parent was then asked to complete a Connors' Parent Rating Scale-Revised (CPRS-R), whilst the child completed the

IQ and spelling tasks. Calculation of the absolute and relative power values from the headset EEG power spectrum data proceeded as described in Study 1.

The headset was fitted, with the active electrode placed at AF3 of the international 10-10 system. Each participant completed five tasks each lasting two minutes each while EEG was recorded, with instructions provided verbally and on the stimulus display computer. In the EC resting task participants were asked to close their eyes for two minutes with instructions “Please sit quietly with your eyes closed”. In the EO resting task participants were asked to look at the fixation cross in the centre of the computer monitor for two minutes, with instructions “Please look at the cross on-screen”. The relaxation task involved a circle that changed its size from large to small over four second cycles presented on the computer monitor, with instructions “Please try to relax. If you breathe in time with the expanding and contracting circle on screen that will help”. In the attention task participants were presented with a small track positioned centrally on the computer monitor, with a small spot travelling around it, with instructions “Please follow the ball around the track and say “now” when the ball goes off the track”. The cognitive load task involved a computer task consisting of a 3 x 4 grid containing six pairs of hidden colour-matched circles. The participants were required to mouse click on each tile to reveal the circle and its colour, and to match it with one other on the grid, until all pairs were revealed and matched, with instructions “Please use the mouse to click in the squares to find circles that match in colour. When you complete the first game, please play again”. Recording sessions were completed in quiet, well-lit, draft-free rooms using identical equipment and procedures regardless of location (i.e. at the participant’s home or at the university).

RESULTS: STUDY 2

The mean age of participants was 10.3 years (SD 2.3) with a mean estimated IQ of 102 (SD 14.4). Each of the children scored within the normal range for spelling ability and also on each subscale of the CPRS-R.

Absolute and relative EEG band powers were examined for the five conditions (EO resting, EC resting, relaxation, attention, cognitive load) with repeated measures ANOVA. Planned simple contrasts within Condition compared activity in the EO resting condition with each other condition separately. Degrees of freedom for all reported effects are (1, 21). Only statistically significant effects are reported here. Mean absolute and relative power in each EEG band for each condition is shown in Figure 5, with a summary of statistical effects provided in Table 1. As shown in Table 1 and Figure 5 (top panel) there were reductions in absolute delta, theta and beta power in the EC resting compared to EO resting condition. For the relaxation condition, absolute delta power was reduced compared to the EO resting condition. Absolute beta was increased in the attention compared to EO resting condition, with a similar increase in the cognitive load compared to the EO resting condition.

As shown in Table 1 and Figure 5 (bottom panel), there was a reduction in relative theta and increase in relative alpha power in the EC compared to the EO resting condition. For the relaxation condition, there was a reduction in relative delta power compared to the EO resting condition. Relative delta and theta were both reduced in the attention condition compared to EO resting, while alpha was increased (note also that relative beta showed a tendency to be increased in the attention condition). For the cognitive load condition, compared to EO resting, relative delta power was decreased while relative alpha and beta power were increased (note that relative theta showed a tendency to be reduced in the cognitive load condition).

-- Insert Figure 5 and Table 1 about here --

DISCUSSION: STUDY 2

This study aimed to examine the sensitivity of headset-processed EEG band power to variations of psychological state in healthy children. The key comparison in relation to state was between the EO and EC resting conditions, with the three active tasks addressing the issue of variation in EO conditions with different processing demands.

The absolute EEG band power results presented here show some correspondence with previously reported effects. Barry et al.^[3] reported increased absolute power in all bands in EC compared to EO conditions in children (mean age 10.6 years), with some effects varying according to scalp recording location (i.e., topography). For example, the increases were larger in the frontal region for delta, larger in the frontal/posterior (compared to central) regions for theta, with a decrease in the frontal region for beta^[3]. The alpha increase was similar at all scalp locations. Unfortunately, post-hoc simple effects tests were not carried out to determine if the frontal effects were significant independent of other regional differences. In the current study, frontal absolute beta was reduced in the EC compared to the EO resting condition in line with previous research^[3, 7], while delta and theta were also reduced. The reduction in absolute beta power would be expected given the reduced processing related neural activity, particularly visual, when the eyes are closed^[8].

While Barry et al.^[3] focused on absolute power, the authors of the current paper were able to access the unpublished relative power data from that paper, which indicated that in the frontal region relative power was reduced in theta, alpha and beta in EC compared to EO conditions, while delta was increased. At a posterior recording location (i.e., Pz), relative power was reduced at delta, theta and beta, in EC compared to EO conditions, with alpha being increased. Here the headset-processed data show significant differences, or mean differences in the appropriate direction, for two of the four frontal region relative power differences and each of the four posterior region differences derived from Barry et al.^[3].

Each of the three EO active tasks placed different processing demands on participants, and it was expected that there would be EEG power differences between these conditions. This was confirmed for each condition, for both absolute and relative EEG data. There was a reduction in absolute power for delta in the relaxation condition, as well as increases in beta for both the attention and cognitive load conditions,

compared to the EO resting condition. The latter results are in line with previous reports of increased beta activity during mental effort ^[4].

Compared to the EO resting condition, there were reductions in relative delta power during each of the active tasks, activity previously reported to decrease with increased stimulus processing ^[3]. The demanding cognitive load condition resulted in increased relative beta power, while the attention condition showed a tendency towards an increase, compared to EO resting, in line with previous reports of increased beta activity during mental effort ^[4]. The tasks with the highest processing demands also showed reductions in relative theta power (significant for attention; tendency for cognitive load). Given the fixed order of task presentation, the increased alpha power in the attention and cognitive load conditions, the last two tasks completed, may correspond with a generally increased state of ease and relaxation in the child participants with time.

These outcomes should be considered in light of the limitations of Study 2, which include the fixed presentation order of the tasks, eye movements in the Attention condition, and broad age-range of participants. It seems that residual eye movement artefact (which would be most evident in low frequency activity) was at a minimum as there were no differences in the low frequency ranges between the EO resting and attention conditions which required explicit eye movements. Age has been shown to influence EEG power within the age-range of the present study ^[9, 10], and while the sample size here does not allow adequate consideration of age effects, it is an avenue for future research.

In summary, the results of Study 2 revealed that headset-derived absolute and relative EEG band power differed in predicted ways for eyes-closed compared to eyes-open resting conditions, as well for eyes-open resting compared to active conditions.

GENERAL DISCUSSION

The present study provides preliminary data concerning the validity of a new method of single-channel EEG measurement, examining concurrent validity via comparisons to a research system, and comparative validity via predictable sensitivity to variations in psychological state. There were strong positive correlations and similar patterns of EO versus EC differences in band power observed between the research system EEG at F3 and the headset data processed on-board or in Scan. The headset-processed absolute and relative EEG band power data showed expected patterns of variation corresponding to particular psychological states. Overall, these results suggest acceptable validity for the new single-channel dry sensor method, but of course there are trade-offs associated with the use of the headset. While the headset is convenient and wireless, and the dry-sensor takes less than 20 seconds to fit, there is a minor trade-off in terms of data quality compared to the research system considered here and a major trade-off in the number of recording locations. Further detailed validation is needed using other research systems and comparison methods. If this work confirms the validity of the EEG recorded by the headset, then it could be used routinely to conduct EEG research with minimal setup time and participant discomfort in a variety of naturalistic settings, which may open up possibilities for new developments in the use of EEG in medication monitoring, training and other applications. Further, the headset may prove especially beneficial in research involving certain clinical populations.

FOOTNOTE

1. Note that two EEG summary scores are also derived by proprietary algorithms. These were developed to provide robust and universal (i.e. not requiring any individualised calibration) indices of two independent psychological state dimensions of “attention” (low to high) and “meditation” (tense to calm). These measures are presented as a value between 0 and 100, enabling their use in a wide range of applications (e.g. providing generalised feedback about ongoing brain activity to the user, and/or as control variables for computer software in the research, educational or entertainment domains).

DISCLOSURE AND CONFLICT OF INTEREST

SJJ, RB and JB have no conflicts of interest in relation to this article.

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TABLES

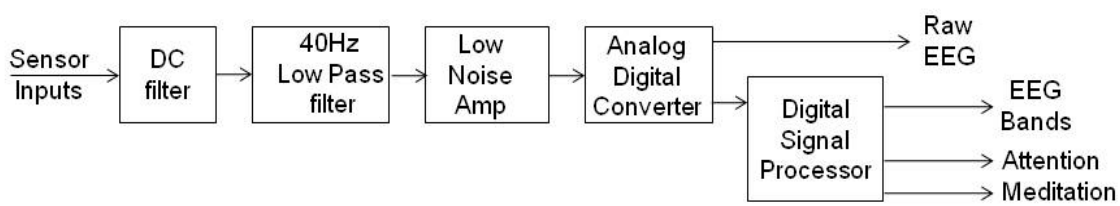
Table 1. A summary of statistical effects for the EEG band power analyses. All reported effects are comparisons with the EO resting condition.

Condition	Band	Absolute	Relative
EC resting	Delta	▼ F=9.2, p<.01	-
	Theta	▼ F=15.5, p<.001	▼ F=4.6, p<.05
	Alpha	-	▲ F=22.9, p<.001
	Beta	▼ F=4.0, p=.06	-
Relaxation	Delta	▼ F=3.8, p=.06	▼ F=11.7, p<.01
	Theta	-	-
	Alpha	-	-
	Beta	-	-
Attention	Delta	-	▼ F=5.6, p<.05
	Theta	-	▼ F=4.9, p<.05
	Alpha	-	▲ F=7.6, p<.05
	Beta	▲ F=8.3, p<.01	^*
Cognitive Load	Delta	-	▼ F=11.8, p<.01
	Theta	-	∨*
	Alpha	-	▲ F=9.3, p<.01
	Beta	▲ F=6.6, p<.05	▲ F=3.9, p=.06

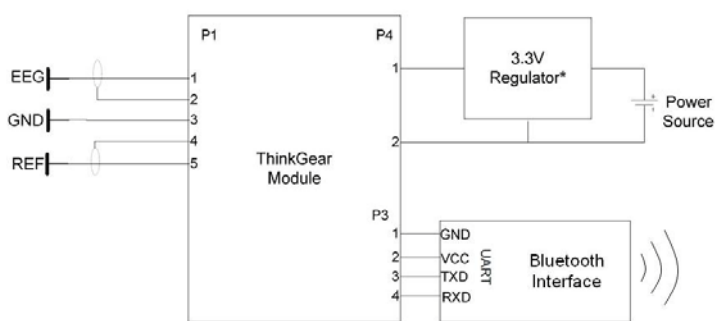
* p. <.09; ▼ or ∨ = reduction; ▲ or ^ = increase,

FIGURES

Figure 1



A.



B.



C.

Figure 2

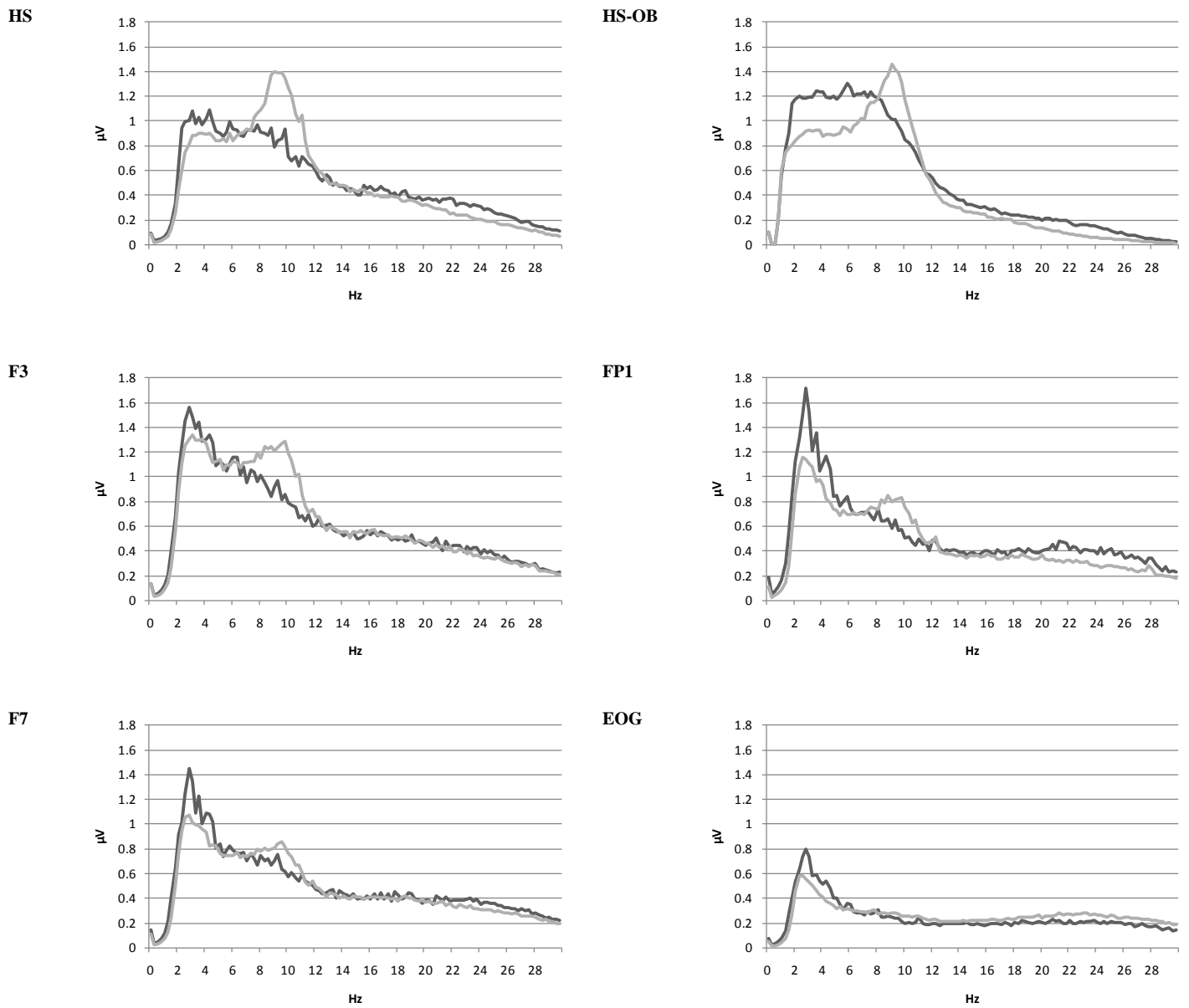


Figure 3

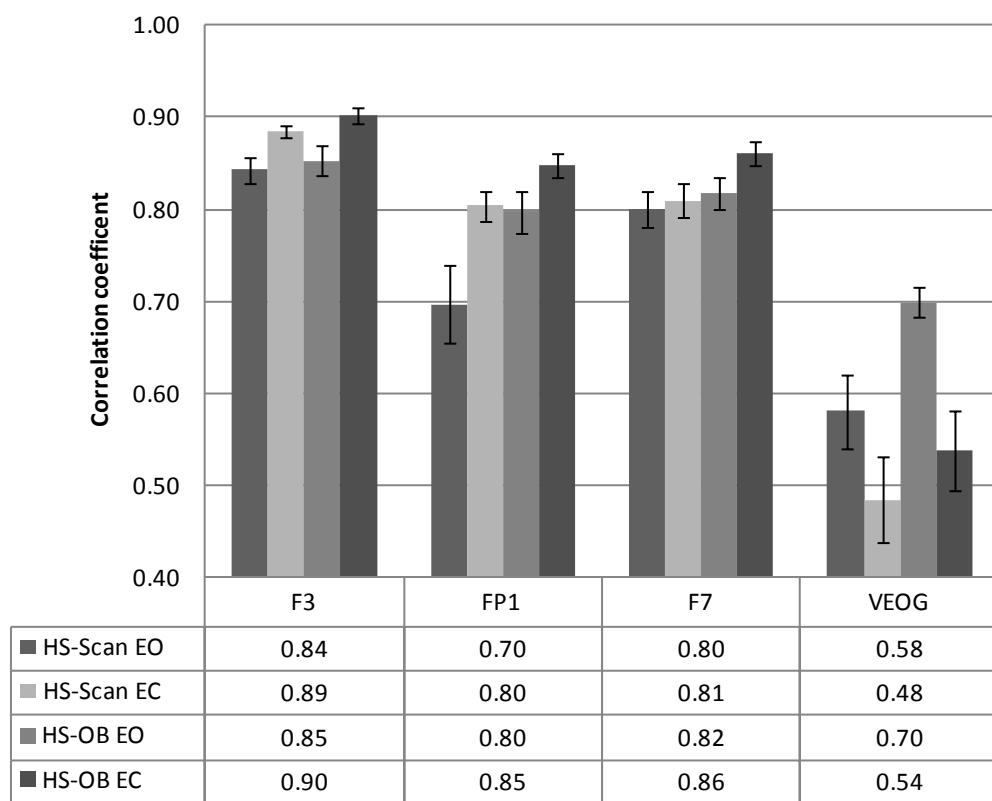
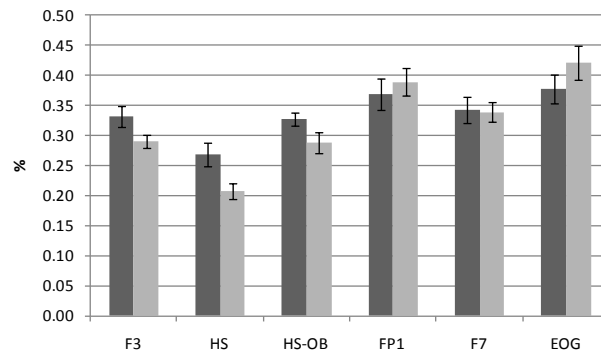


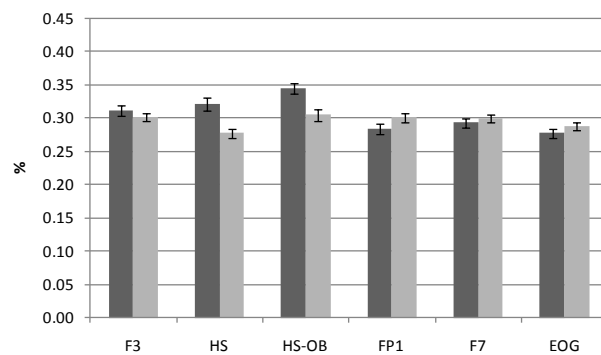
Figure 4

DELTA



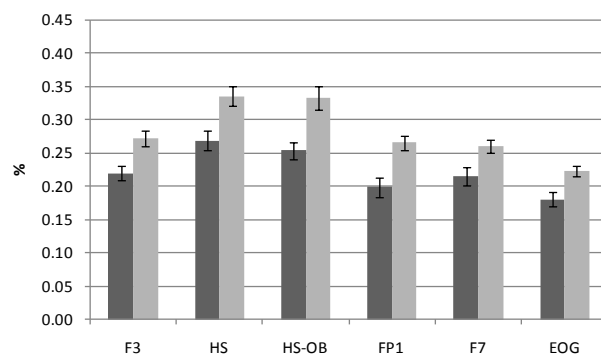
Site (vs. F3) ▼ -- ▲ ▲ ▲
 Site x Cond. (vs. F3) -- -- Rev. ▼ Rev.

THETA



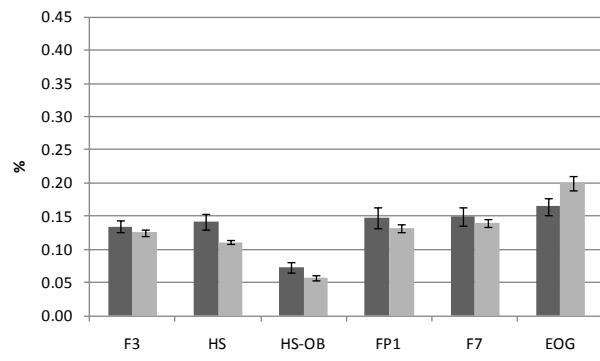
Site (vs. F3) -- ▲ ▼ ▼ ▼
 Site x Cond. (vs. F3) ▲ ▲ Rev. Rev. Rev.

ALPHA



Site (vs. F3) ▲ ▲ ▼ -- ▼
 Site x Cond. (vs. F3) -- ▲ -- -- --

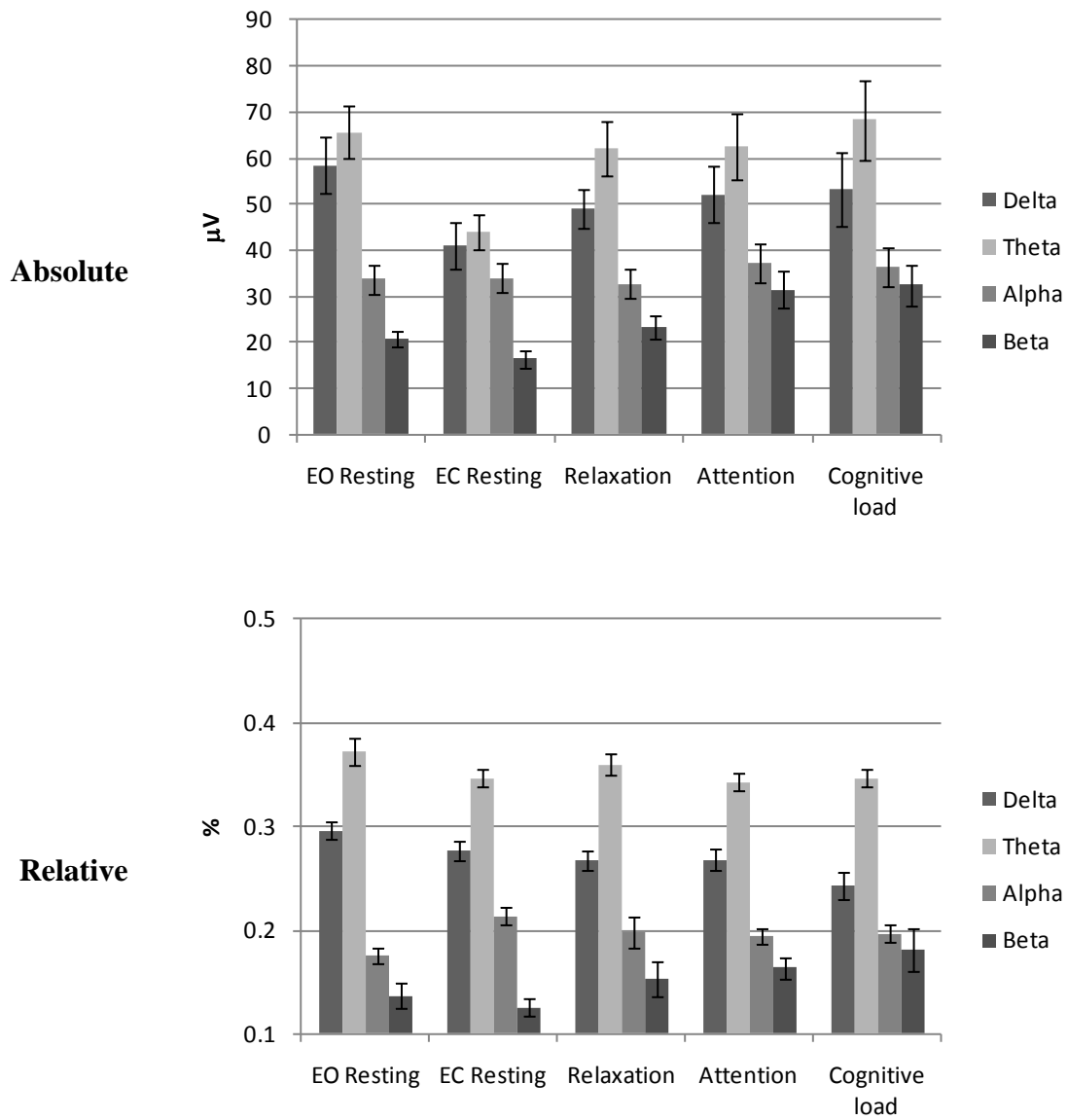
BETA



Site (vs. F3) -- ▼ -- ▲

Site x Cond. (vs. F3) ▲ -- -- -- Rev.

Figure 5



Legend to Figures

Figure 1. The headset consists of the Think-gear microchip as shown in the conceptual block diagram A, and circuit diagram B, housed within, in this case, a set of headphones (termed the MindSet) shown at C. Conductive material reference and ground electrodes are contained within the left ear-pad, while the EEG electrode is embedded in the flexible arm extending from the left headband. Sampling, amplification, filtering and artefact reduction of the raw 128 Hz data are carried out within the embedded microchip, as are Fourier transformations, and transmitted to a display/recording application via Bluetooth.

Figure 2. Averaged EEG power spectra for the EO (black line) and EC (grey line) resting conditions for data recorded simultaneously from the headset and 4 electrodes of the research system. Headset data processed in Scan (HS; top left) and headset data processed on-board the headset (HS-OB; top-right) are shown, along with simultaneously recorded research system EEG processed in Scan at F3 (middle left), FP1 (middle right), F7 (bottom left) and the EOG channel (bottom right). Regardless of recording/processing technique all scalp electrodes show increased alpha activity in the EC compared to EO resting condition; this is not seen in the EOG channel.

Figure 3. Average correlations with the research system data at each site for the EO and EC conditions for headset data processed in Scan (HS-Scan EO, HS-Scan EC) and the headset data processed on-board the headset (HS-OB EO, HS-OB EC). Error bars show standard error.

Figure 4. Relative band power for the EO (dark) and EC (light) resting conditions at each research system site (F3, FP1, F7, EOG) and headset data processed in Scan (HS) and headset data processed on-board the headset (HS-OB). Error bars show standard error. Below each graph is a summary of the statistical effects for the comparison of the relative power at each Site with F3 (top row) and the comparison of the EO vs. EC

difference at each site with F3 (bottom row). Note: -- no difference (i.e. same as F3), ▲ increased, ▼ decreased, Rev. Reversed.

Figure 5. Mean absolute (top) and relative (bottom) EEG power in the delta, theta, alpha and beta bands for each condition, including standard error bars.