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Empirical evidence for the relationship between cognitive workload and attentional reserve

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ABSTRACT

While the concepts of cognitive workload and attentional reserve have been thought to have an inverse relationship for some time, such a relationship has never been empirically tested. This was the purpose of the present study. Aspects of the electroencephalogram were used to assess both cognitive workload and attentional reserve. Specifically, spectral measures of cortical activation were used to assess cognitive workload, while amplitudes of the event-related potential from the presentation of unattended "novel" sounds were used to assess attentional reserve. The relationship between these two families of measures was assessed using canonical correlation. Twenty-seven participants performed a flight simulator task under three levels of challenge. Verification of manipulation was performed using self-report measures of task demand, objective task performance, and heart rate variability using electrocardiography. Results revealed a strong, negative relationship between the spectral measures of cortical activation, believed to be representative of cognitive workload, and ERP amplitudes, believed to be representative of attentional reserve. This finding provides support for the theoretical and intuitive notion that cognitive workload and attentional reserve are inversely related. The practical implications of this result include improved state classification using advanced machine learning techniques, enhanced personnel selection/recruitment/placement, and augmented learning/training.

1. Introduction

The concept of cognitive workload has been long discussed in cognitive psychology. Broadbent (1957) was among the first to discuss the notion that cognitive resources are limited and that a given operation consumes a portion of those resources. Broadbent and others (Kahneman, 1973; Kantowitz, 1987; Sanders, 1979; Wickens, 2002) used this notion of limited cognitive capacity to explain that humans are able to effectively perform tasks that do not completely consume these cognitive resources. In other words, tasks can be successfully performed when there is some capacity in reserve. In the event that the demands of the cognitive system exceed its capacity, a situation of cognitive "overload" emerges and task failure is much more likely to occur.

In a society with ever-increasing informational demands, there is a growing requirement to manage the demand on one's mental systems (i.e., cognitive workload) in an adaptive manner so as to maximize productivity and performance. This is especially true of tasks with relatively high cognitive demand, such as aviation. As a result, investigators have made efforts to measure and monitor cognitive workload using a variety of measurement methodologies. For example, the NASA Task Load Index (TLX), a self-report measure, has been shown to be a valid and reliable indicator of workload (Hart and Staveland, 1988) and is widely used (see (Hart, 2006) for a review). Heart rate variability (HRV) has also been shown to be indicative of cognitive workload (Cinaz et al., 2013; Mehler et al., 2011). Specifically, the root mean square of successive differences (RMSSD) measure of HRV, thought to be reflective of parasympathetic activation, has been found to have significant negative relationships with workload, even during short periods of measurement (Chang and Lin, 2005; Munoz et al., 2015; Thong et al., 2003). Lastly, Gevins and Smith (2003) have noted that electroencephalography (EEG) is a useful tool in

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the measurement of cognitive workload due to its sensitivity to attention and alertness levels via various indicators of cortical activation. Indeed, many investigators have used EEG to measure cognitive workload with success. Gevins and Smith (2003) showed that both theta (5–7 Hz) and alpha band (8–12 Hz) EEG activity have notable relationships with cognitive workload. Hankins and Wilson (1998) also observed that, during the performance of several real-life flight tasks, as task demand increased, alpha power decreased and theta power increased. An experiment by Rietschel et al. (2012) revealed that task difficulty had positive relationships with frontal theta (3–8 Hz) and occipital beta (13–30 Hz) and gamma (30–44 Hz) power and a negative relationship with high alpha (10–13 Hz) power at central and parietal sites. Lastly, several research groups (Gentili et al., Accepted with revision; Hockey et al., 2009; Nassef et al., 2009; Postma et al., 2005) have observed that a ratio between theta and alpha at various midline electrode sites is indicative of cognitive workload. These findings show that EEG frequency-domain measures of cortical activation have strong relationships with cognitive workload.

Within the domain of EEG, time-domain measures in the form of event-related potentials (ERPs) have also been related to task demands. Using a randomized sequence of novel sounds playing in the auditory background of a primary visuomotor task (Tetris®) to generate ERPs, Miller et al. (2011) found that various ERP components, including the N1, the P2, and the P3a, or the "novelty P3" (Polich, 2007), components (all maximal at Cz), shared a negative relationship with task demand, such that as task demand increased, ERP amplitudes reduced. By using these novel, to-be-ignored auditory stimuli as probes of cognitive/attentional resources while participants are engaged in a primary task, it was argued by Miller and colleagues that the stimuli engaged resources beyond those demanded by the primary task, thereby engaging the "spare capacity" described by previous investigators (Kahneman, 1973; Kantowitz, 1987; Wickens, 2002). This spare capacity has been labelled by Miller and colleagues (Miller et al., 2011; Rietschel et al., 2014) as "attentional reserve". How much of this attentional reserve the novel sounds capture, then, may depend upon how much reserve remains during the performance of the primary task. In the context of Miller et al. (2011), as primary task demand increased, less attentional reserve was available to process the novel auditory stimuli, resulting in a decrease in ERP amplitudes.

The studies discussed collectively suggest a simple, yet noteworthy, relationship between cognitive workload and attentional reserve. As task demands increase, cognitive workload increases while attentional reserve decreases. In the present viewpoint, the ERP can be interpreted as being indicative of attentional reserve, while the EEG spectral measures of cortical activation, alongside the NASA TLX and HRV, can be interpreted as being indicative of cognitive workload. Thus, the amplitudes of the ERP, as a measure of attentional reserve, should consistently exhibit inverse relationships with measures of cognitive workload, with a present focus on EEG spectral measures of cortical activation.

While it is theoretically and conceptually understood that cognitive workload and attentional reserve are inversely related, to our knowledge the two concepts have not been explicitly contrasted in an empirical study to illustrate this inverse relationship. One experiment by (Brouwer et al., 2012) did collect both spectral and ERP data simultaneously for the purposes of measuring workload, but the two indicators were not compared in a way that elucidates what aspect of cognitive capacity they represent. Therefore, the aim of the present study is to fill this gap in the literature. Using the visuo-motor task of operating a flight simulator under varying degrees of challenge, and employing the ERP technique used by Miller and colleagues (Miller et al., 2011; Rietschel et al., 2014), we assessed both frequency- and time-domain EEG measures to illustrate the theoretical relationship between cognitive workload and attentional reserve. We also collected self-report and HRV indicators of task demand to provide confidence in the experimental manipulation.

It is hypothesized that EEG spectral measures of cortical activation, taken as a measure of cognitive workload, will have an overall positive relationship with task difficulty. To ensure that all measures of EEG spectral power reflect cortical activation in a directionally unified fashion for purposes of clarity and simplicity, alpha power values, which typically have a negative relationship with cognitive workload, will be multiplied by (-1). In regards to the ERP as a measure of attentional reserve, it is hypothesized that ERP amplitudes will show a negative relationship with task difficulty as a result of fewer attentional resources being available to process the novel sounds. Furthermore, and most importantly, it is predicted that EEG spectral measures of workload and ERP measures of attentional reserve will have a negative relationship with each other. As a manipulation check of task demand, self-report scores (NASA TLX and Visual Analog Scales) and HRV information were gathered alongside the EEG data. We predict that NASA TLX indicators of workload will increase with task demand, while HRV, specifically RMSSD as an indicator of parasympathetic activation, will reduce as task demand increases.

2. Methods

2.1. Participants

Sixty-three (63) healthy participants (seven females) between the ages of 19 and 26 years performed the visuo-motor task of operating a flight simulator at the United States Naval Academy (USNA) using Prepar3D® software (version 1.4, Lockheed Martin Corporation) under three levels of challenge. Of these, 27 participants, all of whom were males, had usable data from both spectral and ERP measures simultaneously. All participants were part of the powered flight program at the USNA, during which participants were expected to perform a successful solo-flight in a small single engine propeller plane upon the completion of the program; all participants had an active interest in becoming pilots. This study was approved by the local institutional review board and written informed consent was obtained from all participants.

2.2. Task description

Three scenarios of varying task demand, or "challenge", were selected from predefined flight training challenges with minor updates and developed with advice from experienced pilots. In each scenario, participants were asked to control a simulated aircraft (T-6A Texan II SP2 USN) with the control stick, throttle, and rudder pedals. The flight was programmed to begin at 0900 virtual time, at N38.5400° latitude and W77.0200° longitude (around Washington, DC, USA), at an altitude of 4000 feet. Each scenario was composed of a 1-min setup period followed by a 10-min flight scenario. The three scenarios (S1, S2 and S3) were defined as follows:

a) S1 ("Easy"): The goal was to maintain the aircraft's current altitude (4000 ft), heading (180°), and airspeed (180 knots) while maintaining such a straight and level course. The weather was defined by no clouds, precipitation, or wind with unlimited visibility.
b) S2 ("Medium"): The goal was to maintain the aircraft's current heading (180°), airspeed (180 knots), and a "wings-level" attitude while continuously making assigned altitude changes (between 4000 and 3000 ft) with ascent and descent rates of 1000 ft per min. The weather was defined by heavy clouds (1/16 mi or 0.1 km of visibility), but no precipitation and no wind.
c) S3 ("Hard"): The goal was to maintain the aircraft's current airspeed (180 knots), while adjusting both heading and altitude. Heading changes consisted of both left (180° to 090°) and right (090° to 180°) turns maintaining a 15° angle of bank. Altitude changes occurred during turns such that participants descended while turning left and ascended while turning right at a rate of 1000 ft per min. The weather was defined by heavy clouds (1/16 mi or 0.1 km of visibility) and a moderate (16 knots) easterly wind, but no precipitation.

As part of an exploratory investigation to assess potential behavioral indicators of attentional reserve, one unexpected or "surprise" event, a flashing "Master Warning" light, occurred from 7 min and 31 s to 7 min and 33 s in each scenario. After the completion of all three scenarios, the participant's detection of this event was assessed, retrospectively.

Scenario sequence was counter-balanced. Novel sounds were generated in a similar way as reported in Miller et al. (2011) using stimuli initially assembled by Fabiani et al. (1996), while using "ear-bud" speakers in place of external computer speakers.

2.3. Procedure

Upon arrival, the participant provided informed consent upon receiving a general explanation of the task. A handedness survey was also administered. Participants were then allowed to familiarize themselves with the flight simulator and the novel sounds for 5 min. Upon completion of the familiarization session, the experimenters prepared the participants for fitment of the EEG cap and ECG sensor. Participants were assigned an initial challenge and provided with relevant instructions. Each participant was provided 1 min to stabilize the plane on the starting parameters of the scenario. After this setup period, the first 10 min scenario, complete with the novel sound stimuli, was executed. Upon completion, participants were provided the Visual Analog Scales (VAS) and National Aeronautics and Space Administration (NASA) Task Load Index (TLX) surveys to report their subjective experience upon completion of the scenario. The same order of procedures was followed until all three challenge levels were completed.

Participants were then disconnected from the equipment, debriefed about the purpose of the experiment, thanked, and excused.

2.4. Data acquisition

2.4.1. Self-report

Two separate self-report measures were used to assess subjective feelings related to task performance: Visual Analog Scales and the NASA TLX. Five visual analog scale questions were posed: (1) Overwhelmed: How overwhelmed was I by the task? (0 = not at all, 100 = completely overwhelmed); (2) Concentration: How much did I have to concentrate to perform the task? (0 = little, 100 = high); (3) Mental Load: How mentally loaded did I feel while performing the task? (0 = not loaded, 100 = completely loaded); (4) Ease: How easy was the task? (0 = extremely easy, 100 = not easy at all/hard); (5) Tiredness: How tired was I after the task? (0 = not tired, 100 = very tired).

The six subscales of the NASA TLX indexed mental demand, physical demand, temporal demand, performance, effort, and frustration. Each subscale provided ranges from 0 to 100 with higher scores reflecting greater demands and performance failures.

2.4.2. Performance

A custom plug-in logging program continuously recorded all of the relevant indicators of performance during flight simulation with a sampling rate of 2 Hz. In particular, the four metrics of airspeed, altitude, heading, and vertical speed were selected due to their relevance and sensitivity to the quality of the pilot's performance.

2.4.3. EEG and ECG

Both EEG and ECG were collected via g.tec data collection hardware (g.tec medical engineering GmbH, Austria). EEG was collected using dry g.sahara sensors from four sites along the frontal (Fz), fronto-central (FCz) central (Cz), and parietal (Pz) midline.[1] ECG was collected with pre-gelled disposable Ag/AgCl sensors from a unipolar placement on the below the bottom left rib. Both EEG and ECG were amplified using the same g.USBamp amplifier and electrode impedances were maintained below 5 kΩ. Data sampling rate was 512 Hz. The right mastoid was employed as the ground for the system and the left ear (A1) was used as the online reference. Data from the right ear (A2) was also recorded for later re-referencing purposes. Lastly, an online band-pass filter was applied with a range of 0.01 Hz to 40 Hz.

2.4.4. Surprise element

Surprise data were collected at the conclusion of all three scenarios for each participant. Participants were told that throughout the scenarios, some lights lit up on the instrument panel. Participants were then asked if they saw any, to point to the one that they saw, and identify the scenarios in which they detected the stimulus. Indication of the correct warning light (Master Warning) for a given scenario was marked as detection of the surprise and yielded a score of "1". Failure yielded a score of "0" for that scenario.

2.5. Data processing

2.5.1. Performance

In each scenario, acceptable performance was achieved by maintaining flight parameters (e.g., altitude, airspeed, heading, bank angle, etc.) within tolerance limits of the goal as specified by experienced pilots. The criteria were defined as follows:

a) S1 (low demand): no more than ± 200 ft from specified altitude, ± 10 knots from specified airspeed, ± 5° from specified heading, and ± 5° from specified bank angle, respectively.
b) S2 (moderate demand): no more than ± 200 ft of assigned altitude at each moment, ± 10 knots of specified airspeed, ± 5° of specified heading, and ± 5° of specified bank angle, ± 500 ft per min of specified ascent and descent rates, respectively.
c) S3 (high demand): no more than ± 200 ft of assigned altitude at each moment, ± 10 knots of specified airspeed, ± 5° of assigned heading at each moment, and ± 5° of specified angle of bank, ± 500 ft per min of specified ascent and descent rates, respectively.

The deviations of each flight parameter were bounded above and below the aforementioned decision boundaries, and then for each metric the average performance per min was calculated by subtracting the area under the bounded deviation curve from the area of the decision boundary once per min. Moreover, to reflect the dynamic quality on the average performance measurement for each flight parameter, the average performance gain was computed per min as the difference between two values, which were the sum of the directional derivatives of a flight parameter and the sum of the maximum directional derivatives of the same parameter assuming the worst. Each average performance gain adjusted the corresponding average performance so that it could differentiate two average performance values even if their areas under the bounded deviation curves were same. The gained average performance values were normalized to be ranged between 0 and 1, where greater values indicate better performance. Lastly, a composite performance index was obtained using the weighted ℓ^2-norm of a vector defined by the selected performance metrics with the number of metrics as the weight. In particular, the selected performance metrics were different in each scenario because of various required conditions in each level of challenge; for instance, all four metrics, three metrics except altitude, and two of them (airspeed and vertical speed) were considered for S1, S2, and S3, respectively.

2.5.2. ECG - HRV

Peaks of the R-wave of the standard PQRST wave complex within the ECG signal were detected using a custom Matlab code (The Mathworks Inc., USA) and inter-beat-interval (IBI) was then extracted from the middle 5 min (300 s) of the 10 min signal. The middle 5 min

[1] Four sites were used in this study as a part of a programmatic effort for application to employ EEG in a field setting. Midline sites were chosen to retain the ability to extract meaningful ERPs while also acquiring meaningful spectral content across several concept-relevant regions-of-interest.

were selected as it allowed the participants to adjust to the demands of each scenario while also avoiding effects of fatigue and boredom at the end of each scenario. Finally, the mean squared differences before and after each interval were calculated and then the square root value was taken to extract the RMSSD value.

2.5.3. EEG - spectral measures

The data were re-referenced to an averaged-ears montage and then processed by employing an IIR filter with a 50-Hz low-pass setting, 48 dB roll-off. Next, the data were segmented into 1 s epochs and mean baseline-corrected (1–1000 ms). All epochs were then visually inspected and those containing significant artifact were removed from further analysis. Next, a Fast Fourier transform was implemented using a Hamming window with 50% overlap; 1-Hz resolution was obtained. Finally, the spectral data were averaged within three two-minute periods (0–2 min, 4–6 min, 8–10 min) to characterize the brain activity during the early, middle, and late stages of each scenario. Finally, the frequency bins were log-transformed and summed to obtain spectral power for the functional bandwidths of interest: Theta (3–8 Hz), low alpha (8–10 Hz), high alpha (10–13 Hz), broadband alpha (8–13 Hz), Beta (13–30 Hz).

2.5.4. EEG - ERP

The data were re-referenced to an averaged ears montage and then were processed by employing an IIR filter with a 20 Hz low-pass setting, 48 dB roll-off. Next, 1-s epochs that were time-locked to the novel sound stimuli were extracted from the time series. These epochs were mean baseline-corrected using the pre-stimulus interval (i.e. − 100–0 ms). The transformed data were then visually inspected and those epochs retaining significant artifact (e.g., eye-blink, muscle activity, etc.) were excluded from further analyses. The remaining epochs were averaged for each of the three conditions. Finally, the average amplitudes for each of the three components of interest were derived for the following time windows: N1 (100–130 ms), P2 (190–240 ms), and P3a (270–370 ms).

2.6. Statistical analysis

The following ANOVA designs employed a Greenhouse-Geisser correction when sphericity was violated and a Benjamini-Hochberg correction for unplanned post-hoc comparisons unless otherwise specified. Conventional degrees of freedom are reported throughout the Results section.

2.6.1. Self-report

A series of ANOVAs with Challenge as the within-subjects factor was employed to test participants' subjective workload measured via the six items in the NASA TLX for each of the three scenarios.

2.6.2. Performance

A one-way ANOVA was performed using the performance metric scores across the three scenarios.

2.6.3. EEG - spectral measures

A series of ANOVAs (3 (Challenge) × 3 (Period) × 4 (Electrode)) was performed to test for effects for all frequency bands of interest. The sole exception to this design was the ratio between frontal theta and parietal alpha which used a 3 (Challenge) × 3 (Period) ANOVA design.

2.6.4. EEG - ERP

A series of ANOVAs (3 (Challenge) × 4 (Electrode)) was performed to test for effects in the three components. Subsequent one-way ANOVAs were conducted for the factor Challenge for each component and, separately, for each electrode.

2.6.5. ECG - HRV

A one-way ANOVA with Challenge as the within-subject factor was performed to test for effects.

2.6.6. Relationship between the ERP and spectral measures

To test the relationship between measures thought to be indicative of workload and measures thought to be indicative of attentional reserve, difference scores were calculated for measures of interest between the three scenarios (S1–S2, S1–S3, and S2–S3) for each measure and Pearson correlations were performed between those difference scores. The use of difference scores was dictated by the desire to assess the relationships between the directionality of the changes across the levels of challenge among the spectral measures of cortical activation and the ERP measures. If the spectral measures exhibit an expected increase as challenge increases (revealing negative difference scores) and the ERP measures exhibit an expected decrease as challenge increases (revealing positive difference scores), the predicted negative relationship between the two measures and the concepts behind them (cognitive workload and attentional reserve, respectively) will be observed. The difference scores also had the added benefit of being normalized as opposed to the raw scores.

Finally, to test whether the family of spectral measures of cortical activation has a negative relationship with the family of ERP measures, collectively, a canonical correlation analysis was conducted. The canonical correlation analysis seeks several linear combinations of the ERP variables and the same number of linear combinations of spectral measure variables in such a way that these linear combinations best express the correlations between the two sets of variables. Importantly, ERP and spectral measures have been argued to be not independent of each other (Intriligator and Polich, 1994; Jansen and Brandt, 1991), making canonical correlation an appropriate analysis. Although the three ERP measures (i.e., N1, P2, and P3) and six spectral measures (i.e., theta, low alpha, high alpha, alpha, beta, and the theta/alpha ratio) were each measured at multiple electrode sites (i.e. Fz, FCz, Cz and Pz), the analysis utilized specific electrode sites for certain measures based upon established literature (i.e., N1 at Cz, P2 at Cz (Allison and Polich, 2008; Dyke et al., 2015), Theta at Fz (Cavanagh and Frank, 2014; Jensen and Tesche, 2002), Alpha (low, high, and broadband) at Pz (Jensen et al., 2002; Sauseng et al., 2005)) and all four sites for measures in which the literature was not unified or did not indicate a specific region/site-of-interest (i.e., P3a (Dyke et al., 2015; Miller et al., 2011; Roy et al., 2015), Beta (Basile et al., 2007; Gola et al., 2013; Ray and Cole, 1985), and the Theta/Alpha ratio either at single electrode sites (i.e., Fz-theta/Fz-alpha) (Gentili et al., Accepted with revision) or across frontal and parietal sites (i.e., Fz-theta/Pz-alpha) (Hockey et al., 2009; Postma et al., 2005)). p-Values were acquired through Roy's largest root (Roy, 1953).

2.6.7. Surprise element

A one-way ANOVA with Challenge as the within-subject factor was applied to the data.

3. Results

3.1. Self-report

The ANOVAs revealed effects for challenge in all self-report measures (statistics shown in Table 1), such that the easy condition was rated easier than the medium condition which was rated easier than the hard condition. Planned comparisons revealed that all levels of challenge were significantly different from all others except the fifth VAS question concerning tiredness, which showed no difference between the easy and medium conditions, and the second NASA TLX question concerning physical demand, which showed only showed a difference between easy and hard conditions (see Fig. 1).

Table 1
ANOVA results for self-report measures.

Measure	F-value	p-Value	η_p^2
VAS1 (overwhelmed)	F(2,50) = 35.064	< 0.001	0.584
VAS2 (concentration)	F(2,50) = 22.430	< 0.001	0.473
VAS3 (mental load)	F(2,50) = 25.115	< 0.001	0.501
VAS4 (difficulty)	F(2,50) = 86.280	< 0.001	0.775
VAS5 (tired)	F(2,50) = 4.007	0.024	0.138
TLX1 (mental demand)	F(2,50) = 49.287	< 0.001	0.663
TLX2 (physical demand)	F(2,50) = 5.762	0.006	0.187
TLX3 (temporal demand)	F(2,50) = 39.358	< 0.001	0.612
TLX4 (failure)	F(2,50) = 34.488	< 0.001	0.580
TLX5 (effort)	F(2,50) = 47.102	< 0.001	0.653
TLX6 (frustration)	F(2,50) = 29.942	< 0.001	0.545

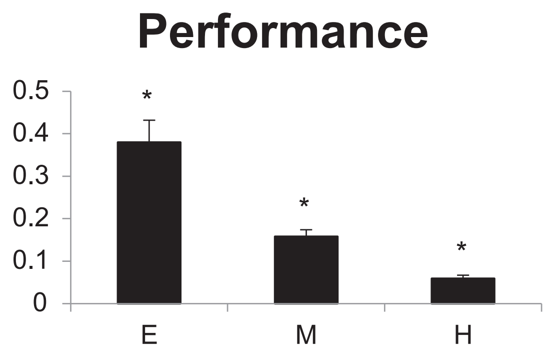

Fig. 2. Performance across the three levels of challenge. *: $p < 0.05$.

3.2. ECG - HRV

The ANOVA featuring the RMSSD measure of HRV failed to reveal any significant differences between the various challenge conditions.

3.3. Performance

The one-way ANOVA revealed a main effect for challenge (F(2,52) = 28.480, $p < 0.001$, $\eta_p^2 = 0.523$) such that participants performed better during the easy condition than the medium condition ($p < 0.001$, d = 1.111) and the hard condition ($p < 0.001$, d = 1.661) and better in the medium condition than the hard condition ($p < 0.001$, d = 1.505; see Fig. 2).

3.4. EEG – spectral measures

Please see Fig. 3 for a graphical representation of these results.

3.4.1. Theta

Theta revealed no main effects for challenge or period. There was a main effect of electrode (F(3,78) = 20.295, $p < 0.001$, $\eta_p^2 = 0.438$), which was superseded by an interaction between period and electrode (F(6,156) = 3.901, p = 0.007, $\eta_p^2 = 0.130$), such that theta power was strongest at frontal electrode sites at the second and third time-points (early vs middle: p = 0.023, d = 0.459; early vs late: p = 0.073, d = 0.351).

3.4.2. Broadband alpha

Broadband alpha revealed a main effect of challenge (F(2,52) = 13.997, $p < 0.001$, $\eta_p^2 = 0.350$, such that easy elicited more alpha power than both medium and hard (easy vs medium: p = 0.033, d = 0.147; easy vs hard: $p < 0.001$, d = 0.328) and medium showed more alpha power than hard (p = 0.004, d = 0.185). There was also a main effect of period (F(2,52) = 18.854, $p < 0.001$, $\eta_p^2 = 0.420$), such that alpha power was lower in the early period of the scenario than the middle ($p < 0.001$, d = 0.213) and late ($p < 0.001$, d = 0.263) periods. Lastly there was a main effect of electrode (F(3,78) = 3.653, p = 0.042, $\eta_p^2 = 0.123$), but this was superseded by an interaction between challenge and electrode (F(6,156) = 3.209, p = 0.016, $\eta_p^2 = 0.110$), such that, while alpha power tended to be stronger at posterior electrode sites compared to frontal electrode sites, frontal sites were more sensitive to differences between the easy and medium levels of challenge, while posterior sites were more sensitive to differences between medium and hard levels of challenge.

3.4.3. Low alpha

Low alpha revealed a main effect of challenge (F(2,52) = 6.269, p = 0.004, $\eta_p^2 = 0.194$), such that easy revealed more alpha power than both medium and hard (easy vs medium: p = 0.021, d = 0.145; easy vs hard: p = 0.004, d = 0.212), which were undifferentiated. There was also a main effect of period (F(2,52) = 6.992, p = 0.005, $\eta_p^2 = 0.212$), such that low alpha increased from the first 2 min to the middle 2 min and to the last 2 min (early vs middle: p = 0.005, d = 0.173; early vs late: p = 0.010, d = 0.190). There were no other significant main effects or interactions.

3.4.4. High alpha

High alpha revealed a main effect of challenge (F(2,52) = 18.013, $p < 0.001$, $\eta_p^2 = 0.409$), such that high alpha power was significantly higher in both the easy and medium condition compared to the hard condition (easy vs hard: $p < 0.001$, d = 0.388; medium vs hard: $p < 0.001$, d = 0.269); easy and medium were undifferentiated. There was also a main effect of period (F(2,52) = 22.812, $p < 0.001$,

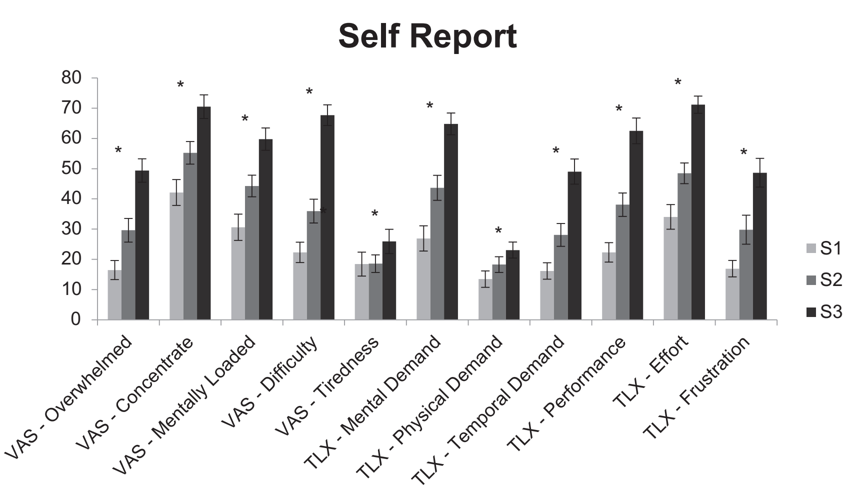

Fig. 1. VAS and NASA-TLX scores across the three levels of challenge. *: $p < 0.05$.

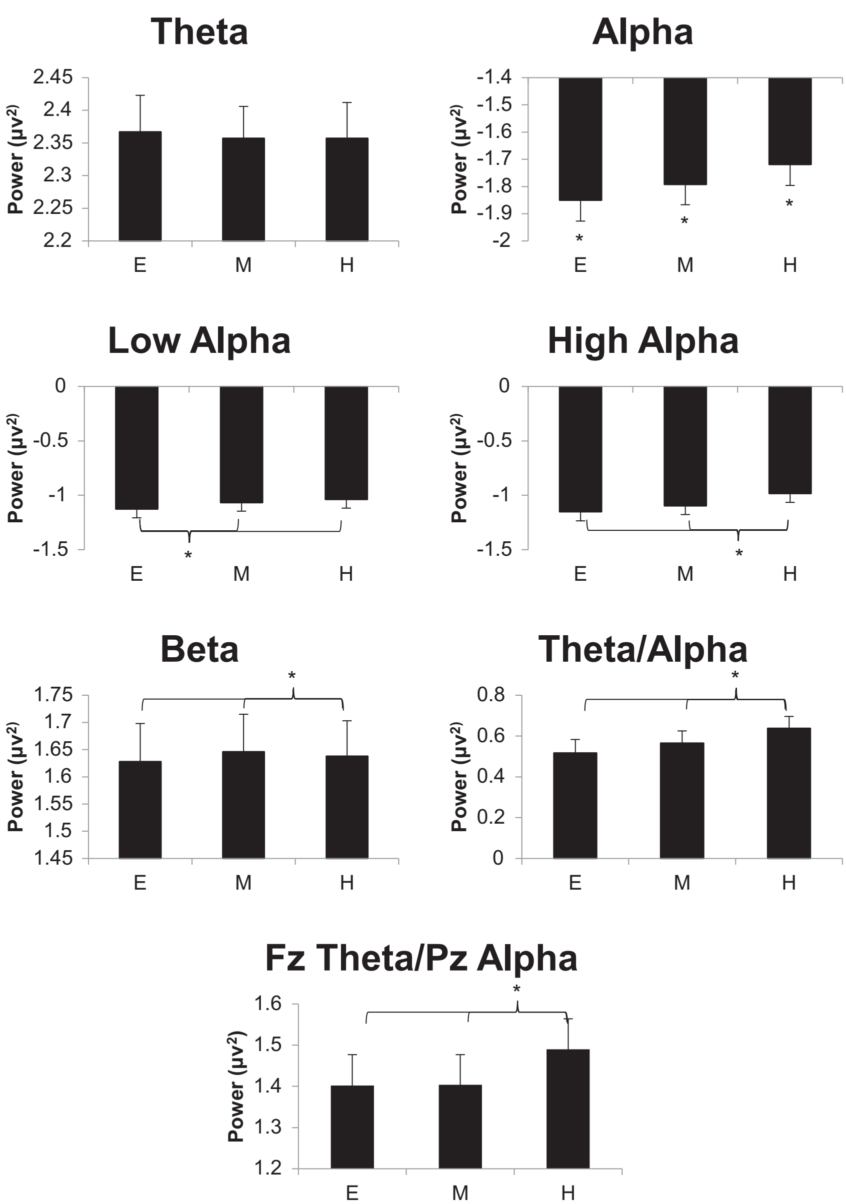

Fig. 3. Spectral power across the three levels of challenge. *: $p < 0.05$.

$\eta_p^2 = 0.467$), such that high alpha increased from the first 2 min to the middle 2 min and to the last 2 min (early vs middle: $p < 0.001$, $d = 0.224$; early vs late: $p < 0.001$, $d = 0.287$); middle and late were undifferentiated. Lastly there was a main effect of electrode ($F(3,78) = 14.964$, $p < 0.001$, $\eta_p^2 = 0.365$) which was superseded by an interaction between challenge and electrode ($F(6,156) = 4.235$, $p = 0.003$, $\eta_p^2 = 0.140$), such that high alpha power was higher at posterior electrode sites compared to frontal electrode sites, but frontal electrode sites appeared to be more sensitive to differences between levels of challenge. There were no other significant main effects or interactions.

3.4.5. Beta

Beta revealed an interaction between period and electrode ($F(6,156) = 3.147$, $p = 0.006$, $\eta_p^2 = 0.108$) such that beta power had a positive relationship with period at the frontal site Fz (early vs late: $p = 0.023$, $d = 0.118$; middle vs late: $p = 0.049$, $d = 0.065$). However, no pairwise comparisons remained significant after the Benjamini-Hochberg correction. There were no other significant main effects or interactions.

3.4.6. Theta/alpha

The theta/alpha ratio measured within a single electrode site revealed a main effect for challenge ($F(2,52) = 10.408$, $p < 0.001$, $\eta_p^2 = 0.286$), such that both easy and medium conditions revealed a smaller theta/alpha ratio than the hard condition (easy vs hard: $p < 0.001$, $d = 0.377$; medium vs hard: $p = 0.010$, $d = 0.235$). There was also a main effect for period ($F(2,52) = 13.052$, $p < 0.001$, $\eta_p^2 = 0.334$), such that the theta/alpha ratio during the early period was larger than in both the middle and late conditions (early vs middle: $p = 0.001$, $d = 0.206$; early vs late: $p < 0.001$, $d = 0.320$). Lastly, there was a main effect for electrode ($F(3,78) = 59.029$, $p < 0.001$, $\eta_p^2 = 0.694$) which was superseded by an interaction between challenge and electrode ($F(6,156) = 6.235$, $p < 0.001$, $\eta_p^2 = 0.193$) such that theta/alpha ratio values were larger at frontal electrodes while being more sensitive to changes in level of challenge at posterior electrodes. There were no other significant interactions.

The frontal-theta/parietal-alpha ratio revealed a main effect of challenge ($F(2,52) = 5.725$, $p = 0.006$, $\eta_p^2 = 0.180$), such that the ratio was larger in both easy and medium conditions relative to the hard condition (easy vs hard: $p = 0.018$, $d = 0.229$; medium vs hard: $p = 0.003$, $d = 0.226$). There was also a main effect for period (F

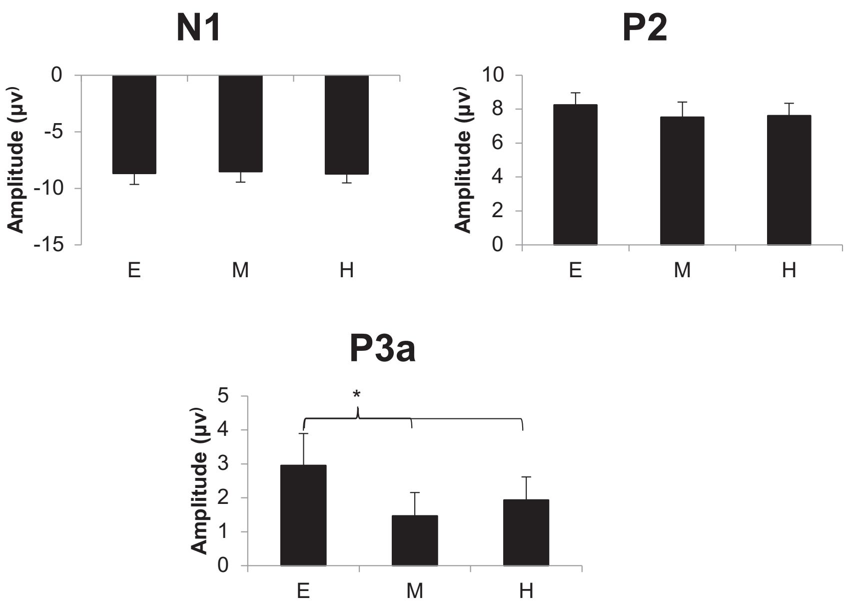

Fig. 4. ERP amplitudes across the three levels of challenge. * = $p < 0.05$ at Cz only.

(2,52) = 6.062, $p = 0.004$, $\eta_p^2 = 0.189$) such that the ratio was smaller in the early period of the task relative to the middle and late periods (early vs middle: $p = 0.018$, $d = 0.133$; early vs late: $p = 0.006$, $d = 0.181$). There was no interaction between challenge and period.

3.5. EEG - ERP

Please see Fig. 4 for a graphical representation of these results.

3.5.1. N1

The amplitude of the N1 component revealed a main effect of electrode ($F(3,78) = 32.359$, $p < 0.001$, $\eta_p^2 = 0.554$) such that N1 amplitude was maximal at the central midline site of Cz, followed closely by the fronto-central midline site of FCz (Fz < FCz: $p < 0.001$, $d = 0.615$; Fz < Cz: $p < 0.001$, $d = 0.705$; FCz > Pz: $p < 0.001$, $d = 0.836$; Cz > Pz: $p < 0.001$, $d = 0.911$). There were no other main effects or interactions. Further planned ANOVAs using individual electrodes failed to reveal any further effects with no clear trends emerging.

3.5.2. P2

The amplitude of the P2 component revealed a main effect of electrode ($F(3, 78) = 21.098$, $p < 0.001$, $\eta_p^2 = 0.448$) such that P2 amplitude was maximal at the central midline site of Cz, followed closely by the fronto-central midline site of FCz (Fz < FCz: $p < 0.001$, $d = 0.742$; Fz < Cz: $p < 0.001$, $d = 0.962$; FCz < Cz: $p = 0.008$, $d = 0.265$; FCz > Pz: $p < 0.001$, $d = 0.888$; Cz > Pz: $p < 0.001$, $d = 1.101$). There were no other main effects or interactions. Further planned ANOVAs using individual electrodes failed to reveal any further effects despite trends for the P2 amplitude to reduce as level of challenge increased.

3.5.3. P3a

There were no main effects or interactions found for the amplitude of the P3a component. However, planned comparisons of P3a amplitudes at electrode Cz revealed a significant effect of challenge $F(2,52) = 3.782$, $p = 0.029$, $\eta_p^2 = 0.127$), such that the easy condition revealed larger P3a amplitudes than the medium or hard conditions (easy vs medium: $p = 0.036$, $d = 0.507$; easy vs hard: $p = 0.031$, $d = 0.399$); medium and hard were undifferentiated.

3.6. Correlations

Bivariate correlations revealed mostly negative relationships between spectral measures of cortical activation and the ERP measures (see Table 2), save for the relationship between P3 amplitude at FCz and Theta band power at FCz which was positive.

Using all spectral measures of cortical activation (Theta (Fz); Alpha (Pz); Beta (Fz, FCz, Cz, & Pz); & Theta/Alpha (Fz, FCz, Cz, Pz, & Fz-Theta/Pz-Alpha)) and all ERP measures (N1 (Cz), P2 (Cz), P3a (Fz, FCz, Cz, & Pz)), the canonical correlations between the ERP and spectral measures of cortical activation are as follows: S1–S2 = − 0.955, $p < 0.001$; S1–S3 = − 0.929, $p = 0.001$; and S2–S3 = − 0.933, $p = 0.001$. There appears to be a strong negative association between the spectral measures of cortical activation and the ERP measures (see Fig. 5).

3.7. Surprise element

The ANOVA featuring the surprise element, the recognition of the Master Warning light on the instrument panel, failed to reveal any differences among the various levels of challenge.

4. Discussion

The goal of this study was to empirically demonstrate the existence of an inverse relationship between measures believed to represent two

Table 2
Significant bivariate correlations. p-Values are uncorrected.

Difference score	ERP - site	Frequency - site	r	p-Value
Easy–medium	P2 - FCz	Low alpha - Pz	− 0.467	0.014
Easy–hard	N1 - Pz	Alpha - Pz	− 0.404	0.037
		High alpha - Pz	− 0.403	0.037
	P2 - FCz	Alpha - Pz	− 0.417	0.031
		Low alpha - Pz	− 0.606	0.001
		Theta/alpha - Fz	− 0.415	0.031
		Theta/alpha - Cz	− 0.421	0.029
	P2 - Cz	Theta/alpha - Fz	− 0.463	0.015
		Theta/alpha - FCz	− 0.428	0.026
		Theta/alpha - Cz	− 0.484	0.010
	P3 - FCz	Theta - FCz	0.464	0.015

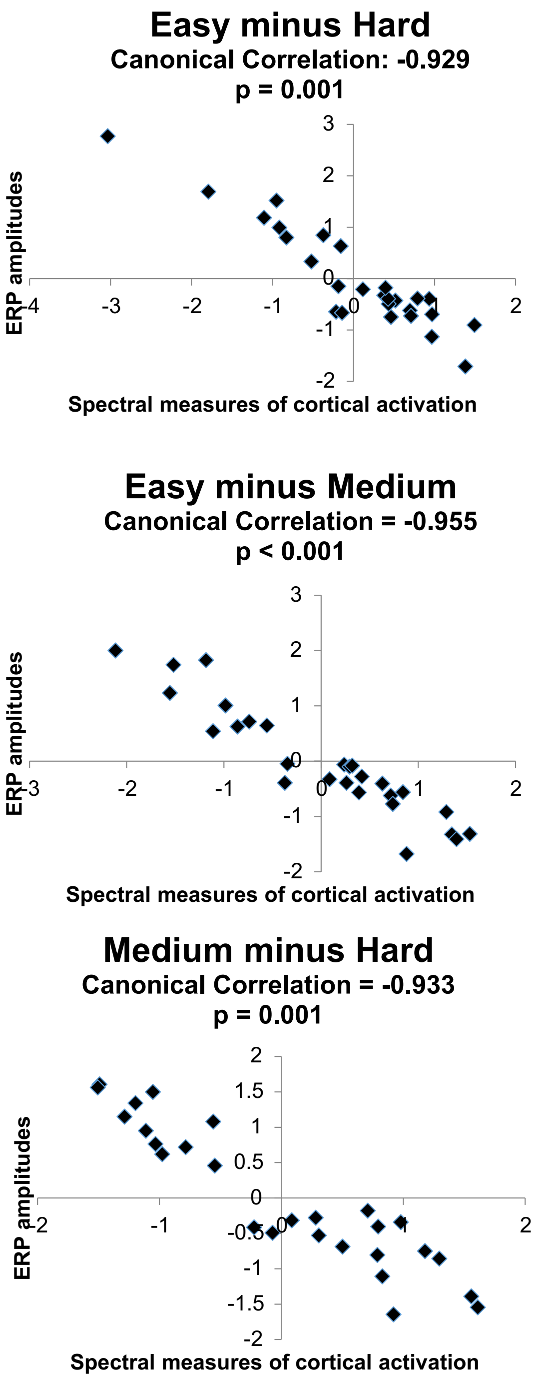

Fig. 5. Scatterplot of individual scores of the canonical correlation for spectral measures of cortical activation (theta, low alpha, high alpha, alpha, beta, and the theta/alpha ratio) and ERP amplitudes (N1, P2, and P3). As canonical correlation always mathematically yields a positive relationship, coefficient values for the spectral measures of cortical activation were multiplied by (− 1) to illustrate the theoretically interpreted negative relationship between cognitive workload and attentional reserve.

opposing elements of cognition: cognitive workload and attentional reserve. Measures of cognitive workload included spectral measures of cortical activation (i.e., theta, alpha, beta, and the theta/alpha ratio) while measures of attentional reserve included ERP amplitudes from "novel" auditory probes (Fabiani et al., 1996; Miller et al., 2011). Broadly, this goal was met; results from the canonical correlation analysis revealed a strong negative relationship between the measures of workload and the measures of reserve. These results offer support for the speculation that the spectral measures of cortical activation and the ERP amplitudes are representative of the concepts of cognitive workload and attentional reserve, respectively.

The self-report results provided confidence of a successful manipulation as all elements of the NASA-TLX and VAS increased as level of challenge increased. Measures of heart rate variability, however, did not reduce with increased task demand as expected. It has been indicated that HRV measures may be related to top-down appraisals of the environment and can be viewed as an index of adaptive regulation of the bodily systems (i.e., cognition, perception, action, physiology) such that HRV is positively related to this adaptive behavior (Thayer et al., 2012; Thayer et al., 2009). The present finding of no difference between levels of challenge may indicate that three levels of challenge did not affect the homeostatic state of the bodily system or the appraisal of the environment despite varying levels of subjective experience, such as differential feelings of effort and frustration. This is encouraging as the flight scenarios employed in this experiment were not intended to manipulate the homeostatic properties of the body; instead they were intended to instigate differential loads on the cognitive system. Lastly, the surprise element, which served as a behavioral correlate of workload, was not sensitive to changes in the level of challenge. This may be due to the positioning of the surprise element in the gauge cluster of the aircraft. Since the gauges were integral to the successful performance of the task, especially during the medium and hard scenarios, visual attention was very often focused on the gauge cluster and within the area the surprise element appeared. Perhaps by placing the surprise element in a less attended to location would yield more expected results.

Among the measures of cognitive workload, alpha, and the theta/alpha ratio behaved as expected, revealing increases in cortical activation and cognitive workload. Theta, however, failed to reveal any effects of interest. Theta has been indeed been linked to cognitive workload (Gevins and Smith, 2003; Hankins and Wilson, 1998; Rietschel et al., 2012), but is more broadly associated with working memory function including integration and encoding (Klimesch, 1999; Sauseng et al., 2010). Given that the presently utilized experimental task is highly complex and the fact that the participants were novices, it is reasonable to think that the demand on working memory would be relatively constant across levels of challenge. This is supported by the fact that previous experiments finding a relationship between theta and workload used simple laboratory tasks (Gevins and Smith, 1999; Rietschel et al., 2012) or skilled participants (Hankins and Wilson, 1998). Similarly, beta failed to reveal any effects of interest. Though beta has been linked with task demand, it has also been associated with a plethora of other constructs that this experiment may or may not have controlled for such as emotional processing (Ray and Cole, 1985), stress (Mauri et al., 2010), movement planning and execution (Klostermann et al., 2007), and attentional processing (Gola et al., 2013). Future work should better control for these myriad elements in order to further investigate beta's relationship with cognitive workload.

Among the ERP amplitude measures of attentional reserve, the P3a revealed an expected effect of challenge, reducing as challenge increases at site Cz. This result supports previous findings showing that the P3a or "novelty P3" decreases in amplitude as cognitive workload increases (Miller et al., 2011; Rietschel et al., 2014). Other components also showed expected directional trends, albeit not significant, similar to Rietschel et al. (2014). The auditory N1 has been indicated of being representative of sensory and early attentional processing (Hansen and Hillyard, 1980) while the P2 has been indicated of being representative of attention allocation (Miller et al., 2011; Picton and Hillyard, 1974) and the orienting response (Kanske et al., 2011) and has been shown to be sensitive to task engagement (Leiker et al., 2016). It is possible that the most challenging scenario elicited a reduction in task engagement because the degree of challenge may have been excessive. This view is supported in part by the P3a results showing a slight increase from the medium scenario to the hard scenario, perhaps indicating a small increase in attentional reserve. These results may serve to highlight the specificity of the P3a as an indicator of attentional reserve. That said, although the effects of the ERP components are necessary to understand how the ERP represents attentional reserve, it is not sufficient to assess the components in isolation and can have utility when analyzed collectively (Roy et al., 2012).

Although the individual measures have their merits, alone they have limited impact on the measurement of our constructs of interest, cognitive workload and attentional reserve. The results of the canonical correlation, which analyzed these variables as members of two distinct "families" of measures, revealed a strong negative relationship between the spectral measures of cortical activation and the ERP measures. To our knowledge, this is the first instance of empirical evidence showing such a relationship between these two theoretically opposed constructs. These findings support previous and intuitive notions (Broadbent, 1957; Kahneman, 1973; Kantowitz, 1987; Wickens, 2002) that capacity is indeed limited and, on the most basic level, consists of two aspects: that which is being used (i.e., cognitive workload) and that which is in reserve (i.e., attentional reserve).

Of course, the approach used in this experiment has limitations. A relatively low sensor count was used for EEG recording with a mind toward practical application. This did, however, place a limit on the analyses that could be performed with the data. A more comprehensive sensor array will benefit future studies of cognitive workload and attentional reserve, specifically if source localization is critical to the research question. Additionally, while ERPs are very useful to investigate the temporal structure of specific cognitive phenomena, they are not well-suited to real-world, real-time application due to the need to average a number of trials to attain a reliable waveform. Work in the realm of single trial ERPs (Delorme and Makeig, 2004; Jung et al., 2001) may lead to change in this regard, but it is worth pointing out this limitation if the focus of attentional reserve measurement is practical application. The last, and perhaps most critical, limitation is a lack of reference or anchor points when investigating and discussing cognitive workload and attentional reserve. While it can be said with some level of confidence based upon the present results that as cognitive workload increases, attentional reserve decreases, science is presently unaware of suitable methodology to assess the upper and lower bounds of human cognitive capacity, nor is it understood how this capacity is impacted by task demand. Without this knowledge, it is unclear the extent of cognitive capacity that is explained by presently utilized metrics. Future research should work to expand the knowledge base in this regard.

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References

Allison, B.Z., Polich, J., 2008. Workload assessment of computer gaming using a single-stimulus event-related potential paradigm. Biol. Psychol. 77 (3), 277–283.
Basile, L.F., Anghinah, R., Ribeiro, P., Ramos, R.T., Piedade, R., Ballester, G., Brunetti, E.P., 2007. Interindividual variability in EEG correlates of attention and limits of functional mapping. Int. J. Psychophysiol. 65 (3), 238–251.
Broadbent, D.E., 1957. A mechanical model for human attention and immediate memory. Psychol. Rev. 64 (3), 205.
Brouwer, A.-M., Hogervorst, M.A., Van Erp, J.B., Heffelaar, T., Zimmerman, P.H., Oostenveld, R., 2012. Estimating workload using EEG spectral power and ERPs in the n-back task. J. Neural Eng. 9 (4), 045008.
Cavanagh, J.F., Frank, M.J., 2014. Frontal theta as a mechanism for cognitive control. Trends Cogn. Sci. 18 (8), 414–421.
Chang, G.H.L.Y.H., Lin, K.P., 2005. Comparison of heart rate variability measured by ECG in different signal lengths. J. Med. Biol. Eng. 25 (2), 67–71.
Cinaz, B., Arnrich, B., La Marca, R., Tröster, G., 2013. Monitoring of mental workload levels during an everyday life office-work scenario. Pers. Ubiquit. Comput. 17 (2), 229–239.
Delorme, A., Makeig, S., 2004. EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. J. Neurosci. Methods 134 (1), 9–21.
Dyke, F.B., Leiker, A.M., Grand, K.F., Godwin, M.M., Thompson, A.G., Rietschel, J.C., ... Miller, M.W., 2015. The efficacy of auditory probes in indexing cognitive workload is dependent on stimulus complexity. Int. J. Psychophysiol. 95 (1), 56–62.
Fabiani, M., Kazmerski, V.A., Cycowicz, Y.M., Friedman, D., 1996. Naming norms for brief environmental sounds: effects of age and dementia. Psychophysiology 33 (4), 462–475.
Gentili, R.J., Jaquess, K.J., Shuggi, I., Oh, H., Lo, L., Tan, Y.Y., Domingues, C., Blanco, J., Rietschel, J., Miller, M., Hatfield, B.D., 2017. Combined assessment of attentional reserve and cognitive effort under various levels of challenge with a dry EEG system. Psychophysiology (Accepted with revision).
Gevins, A., Smith, M.E., 1999. Detecting transient cognitive impairment with EEG pattern recognition methods. Aviat. Space Environ. Med. 70 (10), 1018–1024.
Gevins, A., Smith, M.E., 2003. Neurophysiological measures of cognitive workload during human-computer interaction. Theor. Issues Ergon. Sci. 4 (1–2), 113–131.
Gola, M., Magnuski, M., Szumska, I., Wróbel, A., 2013. EEG beta band activity is related to attention and attentional deficits in the visual performance of elderly subjects. Int. J. Psychophysiol. 89 (3), 334–341.
Hankins, T.C., Wilson, G.F., 1998. A comparison of heart rate, eye activity, EEG and subjective measures of pilot mental workload during flight. Aviat. Space Environ. Med. 69 (4), 360–367.
Hansen, J.C., Hillyard, S.A., 1980. Endogeneous brain potentials associated with selective auditory attention. Electroencephalogr. Clin. Neurophysiol. 49 (3), 277–290.
Hart, S.G., 2006. NASA-Task Load Index (NASA-TLX); 20 years later. In: Paper Presented at the Proceedings of the Human Factors and Ergonomics Society Annual Meeting.
Hart, S.G., Staveland, L.E., 1988. Development of NASA-TLX (Task Load Index): results of empirical and theoretical research. Adv. Psychol. 52, 139–183.
Hockey, G.R.J., Nickel, P., Roberts, A.C., Roberts, M.H., 2009. Sensitivity of candidate markers of psychophysiological strain to cyclical changes in manual control load during simulated process control. Appl. Ergon. 40 (6), 1011–1018.
Intriligator, J., Polich, J., 1994. On the relationship between background EEG and the P300 event-related potential. Biol. Psychol. 37 (3), 207–218.
Jansen, B.H., Brandt, M.E., 1991. The effect of the phase of prestimulus alpha activity on the averaged visual evoked response. Electroencephalogr. Clin. Neurophysiol. 80 (4), 241–250.
Jensen, O., Tesche, C.D., 2002. Frontal theta activity in humans increases with memory load in a working memory task. Eur. J. Neurosci. 15 (8), 1395–1399.
Jensen, O., Gelfand, J., Kounios, J., Lisman, J.E., 2002. Oscillations in the alpha band (9–12 Hz) increase with memory load during retention in a short-term memory task. Cereb. Cortex 12 (8), 877–882.
Jung, T.P., Makeig, S., Westerfield, M., Townsend, J., Courchesne, E., Sejnowski, T.J., 2001. Analysis and visualization of single-trial event-related potentials. Hum. Brain Mapp. 14 (3), 166–185.
Kahneman, D., 1973. Attention and effort: Citeseer.
Kanske, P., Plitschka, J., Kotz, S.A., 2011. Attentional orienting towards emotion: P2 and N400 ERP effects. Neuropsychologia 49 (11), 3121–3129. http://dx.doi.org/10.1016/j.neuropsychologia.2011.07.022.
Kantowitz, B.H., 1987. 3. Mental workload. Adv. Psychol. 47, 81–121.
Klimesch, W., 1999. EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. Brain Res. Rev. 29 (2–3), 169–195. http://dx.doi.org/10.1016/S0165-0173(98)00056-3.
Klostermann, F., Nikulin, V.V., Kühn, A.A., Marzinzik, F., Wahl, M., Pogosyan, A., ... Curio, G., 2007. Task-related differential dynamics of EEG alpha-and beta-band synchronization in cortico-basal motor structures. Eur. J. Neurosci. 25 (5), 1604–1615.
Leiker, A.M., Miller, M., Brewer, L., Nelson, M., Siow, M., Lohse, K., 2016. The relationship between engagement and neurophysiological measures of attention in motion-controlled video games: a randomized controlled trial. JMIR serious games 4 (1).
Mauri, M., Magagnin, V., Cipresso, P., Mainardi, L., Brown, E.N., Cerutti, S., ... Barbieri, R., 2010. Psychophysiological signals associated with affective states. In: Paper Presented at the 2010 Annual International Conference of the IEEE Engineering in Medicine and Biology, (Aug. 31 2010–Sept. 4 2010).
Mehler, B., Reimer, B., Wang, Y., 2011. A comparison of heart rate and heart rate variability indices in distinguishing single task driving and driving under secondary cognitive workload. In: Paper Presented at the Proc Driving Symposium on Human Factors in Driver Assessment.
Miller, M.W., Rietschel, J.C., McDonald, C.G., Hatfield, B.D., 2011. A novel approach to the physiological measurement of mental workload. Int. J. Psychophysiol. 80 (1), 75–78. http://dx.doi.org/10.1016/j.ijpsycho.2011.02.003.
Munoz, M.L., van Roon, A., Riese, H., Thio, C., Oostenbroek, E., Westrik, I., ... Nolte, I.M., 2015. Validity of (ultra-) short recordings for heart rate variability measurements. PLoS ONE 10 (9), e0138921.
Nassef, A., Mahfouf, M., Linkens, D., Elsamahy, E., Roberts, A., Nickel, P., ... Panoutsos, G., 2009. The assessment of Heart Rate Variability (HRV) and Task Load Index (TLI) as physiological markers for physical stress. In: Paper Presented at the World Congress on Medical Physics and Biomedical Engineering, September 7–12, 2009, Munich, Germany.
Picton, T., Hillyard, S., 1974. Human auditory evoked potentials. II: effects of attention. Electroencephalogr. Clin. Neurophysiol. 36, 191–200.
Polich, J., 2007. Updating P300: an integrative theory of P3a and P3b. Clin.

Neurophysiol. 118 (10), 2128–2148.
Postma, M.A., Schellekens, J., Hanson, E.K., Hoogeboom, P.J., 2005. Fz Theta Divided by Pz Alpha as an Index of Task Load During a PC-based Air Traffic Control Simulation. Shaker Publishing, Maastricht, The Netherlands, pp. 1–5.
Ray, W.J., Cole, H.W., 1985. EEG alpha activity reflects attentional demands, and beta activity reflects emotional and cognitive processes. Science 228, 750–752.
Rietschel, J.C., Miller, M.W., Gentili, R.J., Goodman, R.N., McDonald, C.G., Hatfield, B.D., 2012. Cerebral-cortical networking and activation increase as a function of cognitive-motor task difficulty. Biol. Psychol. 90 (2), 127–133. http://dx.doi.org/10.1016/j.biopsycho.2012.02.022.
Rietschel, J.C., McDonald, C.G., Goodman, R.N., Miller, M.W., Jones-Lush, L.M., Wittenberg, G.F., Hatfield, B.D., 2014. Psychophysiological support of increasing attentional reserve during the development of a motor skill. Biol. Psychol. 103, 349–356.
Roy, S.N., 1953. On a heuristic method of test construction and its use in multivariate analysis. Ann. Math. Stat. 220–238.
Roy, R., Bonnet, S., Charbonnier, S., Campagne, A., 2012. Time-on-task effect on workload level discriminability through electroencephalography. In: Paper Presented at the 18th International Conference on Biomagnetism (BIOMAG 2012).
Roy, R.N., Bonnet, S., Charbonnier, S., Jallon, P., Campagne, A., 2015. A comparison of ERP spatial filtering methods for optimal mental workload estimation. In: Paper Presented at the 2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC).
Sanders, A., 1979. Some remarks on mental load. In: Mental Workload. Springer, pp. 41–77.
Sauseng, P., Klimesch, W., Schabus, M., Doppelmayr, M., 2005. Fronto-parietal EEG coherence in theta and upper alpha reflect central executive functions of working memory. Int. J. Psychophysiol. 57 (2), 97–103.
Sauseng, P., Griesmayr, B., Freunberger, R., Klimesch, W., 2010. Control mechanisms in working memory: a possible function of EEG theta oscillations. Neurosci. Biobehav. Rev. 34 (7), 1015–1022.
Thayer, J.F., Hansen, A.L., Saus-Rose, E., Johnsen, B.H., 2009. Heart rate variability, prefrontal neural function, and cognitive performance: the neurovisceral integration perspective on self-regulation, adaptation, and health. Ann. Behav. Med. 37 (2), 141–153.
Thayer, J.F., Åhs, F., Fredrikson, M., Sollers, J.J., Wager, T.D., 2012. A meta-analysis of heart rate variability and neuroimaging studies: implications for heart rate variability as a marker of stress and health. Neurosci. Biobehav. Rev. 36 (2), 747–756.
Thong, T., Li, K., McNames, J., Aboy, M., Goldstein, B., 2003. Accuracy of ultra-short heart rate variability measures. In: Paper Presented at the Engineering in Medicine and Biology Society, 2003. Proceedings of the 25th Annual International Conference of the IEEE.
Wickens, C.D., 2002. Multiple resources and performance prediction. Theor. Issues Ergon. Sci. 3 (2), 159–177.