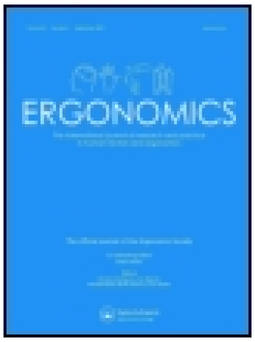

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Ergonomics

ISSN: 0014-0139 (Print) 1366-5847 (Online) Journal homepage: http://www.tandfonline.com/loi/terg20

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To cite this article: Pavle Mijović, Vanja Ković, Maarten De Vos, Ivan Mačužić, Petar Todorović, Branislav Jeremić & Ivan Gligorijević (2016): Towards Continuous and Real-Time Attention Monitoring at Work: Reaction Time versus Brain Response, Ergonomics, DOI: 10.1080/00140139.2016.1142121

To link to this article: http://dx.doi.org/10.1080/00140139.2016.1142121

Publisher: Taylor & Francis
Journal: *Ergonomics*
DOI: http://dx.doi.org/10.1080/00140139.2016.1142121

Towards Continuous and Real-Time Attention Monitoring at Work: Reaction Time versus Brain Response

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Acknowledgments

This research is financed under EU project “Innovations Through Human Factors in Risk Analysis and Management”, Marie Curie Actions FP7-PEOPLE-2011-ITN-InnHF-289837. We would further like to acknowledge company “Gomma Line” (Serbia), for their assistance and advisory during the experimental setup phase.

Disclosure Statement

In accordance with Taylor & Francis policy and my ethical obligation as a researcher, I am reporting that one of the co-authors, Ivan Gligorijević, is also associated with the mBrainTrain Company, supplier of wireless EEG system ‘SMARTING’ used in this study. However, no financial or other conflicting interests arise from this fact and I have in place an approved plan for managing any potential conflicts that might appear.

Towards Continuous and Real-Time Attention Monitoring at Work: Reaction Time versus Brain Response

Continuous and objective measurement of the user attention state still represents a major challenge in the ergonomics research. Recently available wearable electroencephalography (EEG) opens new opportunities for objective and continuous evaluation of operators’ attention, which may provide a new paradigm in ergonomics. In this study, wearable EEG was recorded during simulated assembly operation, with the aim to analyse P300 event-related potential (ERP) component, which provides reliable information on attention processing. In parallel, reaction times (RTs) were recorded and the correlation between these two attention-related modalities was investigated. Negative correlation between P300 amplitudes and RTs has been observed on the group level (p<.001). However, on the individual level, the obtained correlations were not consistent. As a result, we propose the P300 amplitude for accurate attention monitoring in ergonomics research. On the other hand, no significant correlation between RTs and P300 latency was found on group, neither on individual level.

Keywords: attention; wireless EEG; event-related potentials; P300; reaction times

Practitioner Summary: Ergonomic studies of assembly operations mainly investigated physical aspects, while mental states of the assemblers were not sufficiently addressed. Presented study aims at attention tracking, using realistic workplace replica. It is shown that drops in attention could be successfully traced only by direct brainwave observation, using wireless electroencephalographic (EEG) measurements.

Introduction

Studies in the Human factors and ergonomics (HFE) regarding mental, cognitive and emotional functions are perceived through theoretical constructs and are still dependent on behavioural indicators (Farfowicz and Marek 2007), subjective questionnaires and measurements of operators' overall performance (Parasaruman 2003). However, these methods are often unreliable (Lehto, and Landry 2012; Parasaruman and Rizzo 2008; Parasaruman 2003; Simpson et al. 2005). Additionally, they are unable to provide real-time and continuous performance and attention measurement at work places (Jagannath and Balasubramanian 2014), where the continuous focus is essential (Jung et al. 1997). On the other hand, wearable electroencephalography (EEG) can provide the possibility to continuously and objectively assess the attention level of the operators, which may provide a new paradigm in ergonomics research for human performance monitoring.

In the early years of industrialization, accidents were reported mainly in terms of technological malfunctions, ignoring the human element as the cause (Gordon 1998). However, as technology became increasingly reliable, failures related to it have been dramatically reduced, attributing majority of the remaining accidents to human elements in the system (Stanton et al. 2010). Regardless of all the technological advancements, resulting in the increase of the process automation, majority of the manufacturing processes still rely on human participation and intelligence (Hamrol, Kowalik, and Kujawińsk 2011). This is especially notable in manual assembly tasks, which are still unavoidable in variety of modern industries (Hamrol, Kowalik, and Kujawińsk 2011; Michalos et al. 2010; Tang et al. 2003).

Throughout the industrial history, studies of human performance in assembly tasks were mainly concerned with postures of the operators (Fish, Drury, and Helander 1997; Li and Haslegrave 1999; Rasmussen , Pejtersen, and Goodstein 1994), which are still one of the main causes for work related musculoskeletal disorders (Leider et al.

2015). However, far less attention has been dedicated to the cognitive and perceptual factors that can cause errors in operating (Fish, Drury, and Helander 1997). For example, the decrease in attention often precedes human error (Arthur, Barret, and Alexander 1991; Kletz 2001; Reason 1990; Shappell and Wiegmann 2000; Wallace and Vodanovich 2003), and therefore, its timely detection could help avoidance of dangerous situations including workers injuries, material damage and even accidents with casualties.

In order to provide more objective parameters of workers cognitive state, Parasuraman (2003) proposed a novel path in ergonomics research, which was tentatively named neuroergonomics (Parasuraman, 2003). The main objective of neuroergonomics is to objectively assess how the brain carries out everyday and complex tasks in naturalistic work environments (Parasuraman 2003; Mehta and Parasuraman 2013). In its essence the neuroergonomics is able to provide precise analytical parameters depending on the work efficiency of individuals, by directly investigating relationship between neural and behavioural activity (Fafrovicz and Marek 2007). In this way, unreliable user state evaluation based on theoretical constructs, which are mostly describing cognitive states of the workers related to the task execution, can be avoided (Fafrovicz and Marek 2007).

Widely used technique for neuroergonomics studies was functional near infrared spectroscopy (fNIRS), mainly due to its high mobility and low cost. However, fNIRS provide indirect metabolic indicators of neural activity and it has low temporal resolution (Mehta and Parasuraman 2013). On the other hand, techniques for direct measurement of neural activity that provide high temporal resolution, EEG and event related potentials (ERPs), were moderately mobile and the most of the research was confined in the laboratory space or simulators, thus limiting the usefulness of such a measurements in neuroergonomics research (Mehta and Parasuraman 2013; Fu and Parasuraman 2008). However, as technology advanced EEG became increasingly mobile and eventually wearable, providing possibility to directly observe neural activity in applied environments (Wascher, Heppner, and Hoffmann 2014; Mijović et al. 2014).

EEG provides the possibility to both timely and objectively detect the critical behaviour of humans (e.g. drops in attention, error, etc.) and it has been confirmed as a reliable tool in estimating ones' cognitive state (Klimesch et al. 1998; Luck,Woodman, and Vogel 2000; Murata, Uetake, and Takasawa 2005; Yamada 1998). Analysis of the ERPs, extracted from continuous EEG recording, represents commonly employed method in evaluating ones' neural activity (Hohnsbein, Falkenstein and Hoormann 1998). Picton et al. (2000) defined ERPs as 'voltage fluctuations that are associated in time with certain physical or mental occurrence'. ERP components are usually defined in terms of polarity and latency with respect to a discrete stimulus, and have been found to reflect a number of specific perceptual, cognitive and motor processes (Brookhuis and De Waard 2010). In that sense, so-called P300 (also called P3) component is represented by the positive deflection in terms of voltage, appearing around 300ms after the stimulus presentation (Gray et al. 2004; Polich and Kok 1995). Further, the P300 component is often used to identify the depth of cognitive information processing, being strongly related to the attention level (De Vos, Gandras and Debener 2014; Johnson 1998; Polich 2007). It is usually considered that P300 component is not influenced by the physical attributes of the stimuli (Grey et al., 2004; Murata, Uetake and Takasawa 2005). However, the recent study demonstrated that if P300 is indeed equivalent to centro-parietal positivity (CPP) in the gradual target detection task, physical attributes could influence the P300 component (O'Connell, Dockree and Kelly 2012). Another modality which can provide a continuous-like assessment of human attention level is a behavioural measure of the reaction times (RTs, [Larue, Rakotonirainy, and Anthony 2010; Sternberg 1969]). RT represents a time interval from the indicated start of operation (stimulation), until the moment of the action initiation and the main reason for wide usage of RT measurements is that they are easy to obtain and simple to interpret (Salthouse and Hedden 2002). However, the major drawback of experiments involving RT is that they usually consist of a stimulus followed by the response, without direct possibility to observe the mental processing that occurs between stimuli (Luck,Woodman, and Vogel 2000; Young and Stanton 2007).

Although Parasaruman (1990) proposed the idea of applying ERP recording in operational environments, in order to address various HFE problem areas, only very recent studies provided possibility of recording ERPs in applied environments by utilizing available wireless connections (Debener et al. 2012; De Vos, Gandras, and Debener 2014; Wascher, Heppner, and Hoffmann 2014). This finally allowed merging EEG with the guiding principle of neuroergonomics, and examination of how the brain carries out complex everyday work tasks in realistic environments (Parasaruman and Rizzo 2008). Present study proposes a ‘new paradigm’ in ergonomics research through utilisation of ERP measurement in naturalistic workplace environment, where manual assembly operation was simulated. This is the first study (up to our knowledge), which utilize a wireless 24-channel EEG recordings for ERP extraction in naturalistic environment for purpose of studying the operators attention. The main aim of this study is proposal of novel methodology for attention monitoring of an assembly worker, which is based on real-time EEG signal acquisition. As the main disadvantage of the EEG measurement, its immobility, is now overcome we strongly believe that its utilization in the real workplace environments will be ubiquitous in the years to come.

In present study we investigated the propagation of the P300 ERP component peak amplitude and latency in order to assess the operators' level of attention, utilizing recently available mobile EEG equipment that did not alter the working process and enabled a 'truly unobtrusive' paradigm. In parallel, the propagation of behavioural component (RT) was examined. We tested the hypothesis that the decreased level of attention, reflected in the reduced P300 amplitude, would also be followed by the longer duration of RT, as the operator will need more time to complete the operation, and vice versa. We further examined the relationship between the RTs and P300 peak latency, in order to investigate whether the RT duration would influence the latency of the P300 peak. To address the problem of realistic work environment, an authentic replica of an existing assembly work position from a car subcomponent manufacturer was created.

Materials and Methods

Participants

Fourteen healthy subjects, all right-handed and white skin colour males, of age between 19 and 21 years volunteered as participants in the study. Two participants were excluded from further analysis, due to abnormalities during the recording. Participants had no past or present neurological or psychiatric conditions and were free of medication and psychoactive substances. They have agreed to participation and signed informed consent after reading the experiment summary. The Ethical committee of the University of Kragujevac approved the study and procedures for the participants.

Experimental Task

Our laboratory simulation replicates the production of rubber hoses used in the hydraulic brake systems in automotive industry. Full-scale replica of the specific workplace from car sub-component manufacturing company has been created in the laboratory of the Department for Production Engineering, University of Kragujevac (Figure 1). All major elements have been included, replicating microclimate conditions from manufacturing company (including ambient temperature, air humidity, noise and luminance), while preserving respective spatial ratios. An important notion is that, in order to access the P300 ERP component a slight functional modification for this specific workplace was introduced, without significantly altering the work routine. Instead of the information which the workers would receive in the real workplace, here the participants were receiving information regarding the initiation of their assembly operation as they were presented with the 'go/no-go' psychological test, simultaneously with the simulated assembly operation (explained in detail in the subsequent section).

[Figure 1 near here]

In the production process, an operator is carrying out the crimping operation in order to assemble the metal extension to the rubber hose. This single operation consists of eight simple steps (actions). Step by step simulated operation, carried out by participants in replicated working environment, is graphically presented in Figure 2 and explained in details further in the text.

Major production steps can be summarized as follows: firstly, the information in the form of visual stimulus, is presented to the participant (step 1), upon which he is instructed to instantly initiate the operation by taking the metal part (step 2) and the rubber hose (step 3). Following this, participants should place the metal part on the hose (step 4), which is followed by placement of the incomplete element inside the crimping machine (step 5). Participant then proceeds by promptly pressing the pedal, upon which the improvised machine replicates the real machines' crimping sound in the duration of the 3500ms (step 6). Upon completion of the simulated crimping process, the participant removes the component and places it in the box with completed parts (step 7). Finally, following these steps, the participant sits still, waiting for the subsequent stimulus (step 8) indicating the next-in-line operation.

[Figure 2 near here]

Although the process is comprised of eight sub-actions, the whole operation lasts less than ten seconds and a single operator completes between 2500-3000 elements during a work shift. Therefore, this workplace represents a typical example of a repetitive, monotonous operational task in industrial assembly settings.

Preparation and Experimental Procedure

Each of the participants arrived in the laboratory at 9:00 a.m. Upon carefully reading the experiment summary and signing the informed consent for participation in the study, participants started the 15-minute training session, in order to become familiar with the task, following which they confirmed the readiness to start the experiment. Finally, EEG cap and amplifier were mounted on the participants' head and the recording started around 9:30 a.m.

Participants were seated in the comfortable chair in front of an improvised workplace, while the modified version of Sustained Attention to Response Task (SART) was presented on the 24" screen from a distance of approximately 100 cm. The screen was height adjustable and the centre of the screen was set to be in level with participants' eyes.

In short, SART paradigm proposed by Robertson et al. (1997) consists of sequentially presenting the digits from '1' to '9'. Participants are required to respond to each digit by the single button press upon its presentation, with the exception of the digit '3', which is marked as a 'no-go' stimulus and participants are instructed to withhold the response. However, since in this study the original paradigm would impede the simulation of assembly operation, it was not possible to require speeded responses in (literal) sense of discrete button presses. Instead, Participants were to remain still until the stimulus appeared on the screen and only then initiate the described operation. Further on, the digits were presented randomly to the participants, so that participants could not predict the appearance of the 'no-go' stimuli. Given all these changes, in further text we will refer to this paradigm as Numbers. In this way, in the Numbers paradigm participants were instructed to pay attention at all 'go', which are regarded here as the target stimuli, and to withhold their action otherwise.

All stimuli were presented for 1000ms in a white font on a black screen background. The total experiment per subject duration was around one and a half hour during which 500 stimuli were presented in total (450 'go' trials and 50 'no-go' trials). Sequence of stimuli was randomized with the condition that forbade two consecutive appearances of the 'no-go' stimuli. A mean inter-stimulus interval (ISI) on 'go' trials was 11318ms (STD = 529ms) , while the ISI between 'no-go' and the next 'go' trial was 2970ms (STD = 48ms), including a jitter between the end of operation and presentation of following stimuli that was set to be in the 1000-2000ms range. Further, similarly to Dockree et al. (2007), five randomly allocated digit sizes (60, 80, 100, 120 and 140 points in Arial text font) were presented to increase the demands for processing the numerical value and to minimize the possibility of setting a search template for some perceptual feature of the 'no-go' trial.

The task specifications were programmed in Simulation and Neuroscience Application Platform (SNAP, https://github.com/sccn/SNAP). As explained in Bigdely-Shalmo et al. (2013), SNAP is a python-based experiment control framework that is able to send markers as strings to Lab Streaming Layer (LSL, https://code.google.com/p/labstreaminglayer/). LSL is a real-time data collection and distribution system that allows multiple continuous data streams as well as discrete marker timestamps to be acquired simultaneously.

EEG recording

EEG data acquisition was performed using state-of-the-art wireless and wearable EEG system 'SMARTING' (mBrainTrain, Serbia), with the sampling frequency of 500 Hz. The small in size and lightweight EEG amplifier (80x50x12mm, 55gr) is tightly connected to a 24-channel electrode cap (Easycap, Germany), at the occipital site of the participants' head using an elastic band. The connection between the EEG amplifier and recording computer was obtained using Bluetooth connection, and the data were streamed to the mentioned LSL recorder. The design of the cap-amplifier unit ensured minimal isolated movement of individual electrodes, cables, or the amplifier, which strongly reduced electromagnetic interference and movement artefacts. Further, small dimensions of the recording system provided full mobility and comfort to the participants, as movement constraints were not imposed. The electrode cap contained sintered Ag/AgCl electrodes that are placed based on the international 10-20 System. The electrodes were referenced to the FCz and the ground electrode was AFz. During the recording, the electrode impedances were kept below 5kΩ, which was confirmed by the device acquisition software.

Data Analysis

The RTs were calculated as the difference between timestamps from the operation initiation and actual beginning of the crimping process. In other words, RTs are here regarded as the time elapsed between the stimulus presentation (step 1) and the moment when participant presses the pedal (step 6), as indicated in Figure2.

EEG analysis was performed offline using EEGLAB (Delorme and Makeig 2004) and MATLAB (Mathworks Inc., Natick, MA). EEG data were first bandpass filtered in the 1-35 Hz range. The EEG signals were then re-referenced to the average of Tp9 and Tp10 electrodes. Further, an extended Infomax Independent Component Analysis (ICA) was used to semi-automatically attenuate contributions from eye blink and (sometimes) muscle artifacts (as explained in De Vos, De Lathauwer, and Van Huffel [2011]; De Vos et al. [2010]; Viola et al. [2009]). ERP epochs were extracted from continuous EEG signal in the time range -200 to 800ms with respect to timestamp values of stimuli. Baseline values were corrected by subtracting mean values for the period from -200 to 0ms from the stimuli. The identified electrode sites of interest for the ERP analysis in this study were Fz, Cz, CPz and Pz, as the P300 component is usually distributed and is most prominent over the central and parieto-central scalp locations (Picton 1992).

ERP Processing – P300 Amplitudes and Latencies

In the ERP analysis, we have firstly calculated the mean grand average (GA) values of the ERPs for the ‘go’ and ‘no-go’ conditions. The GA methodology provides only the single value for the whole measurement period, thus the continuous evaluation of the ERP components was impossible. On the other hand, single trials ERPs could be used for the continuous evaluation of ERP components, but they would have low signal-to-noise (SNR) ratio. However, it has been reported that good quality ERPs could be obtained with as few as 11-repeated stimulus trials (Humphrey and Kramer 1994; Prinzel et al. 2003). Therefore, in order to create a trade-off between reliability and temporal resolution we decided to employ a moving window on single trial ERPs elicited by ‘go’ condition, averaging the last 15 trials for selected electrodes. The usage of this one-trial-step overlapping window left the total of 435 averaged ERPs for further analysis.

The P300 component obtained in this study was bifurcated containing two subcomponents, P3a and P3b. Whilst the P3a is more frontally distributed, the P3b is more prominent in the centro-parietal region (Polich, 2007). However, their latency vary depending on the stimulus events which elicit them, nature of task, population of participants included in the study, etc. In order to quantify and examine the propagation of P3a and P3b component amplitude and latency for 435 averaged ERPs, the following strategy was used: for the P3a and P3b sub-components, the latency of the maximum peak on the grand averaged ERPs for each subject was found and the 100ms interval window surrounding the peak was chosen for the calculation of the amplitude, utilizing mean peak amplitude method proposed by Luck (2005). Similarly, the latency value on each of the 435 averaged ERPs was calculated using peak latency measures (Luck, 2005).

Comparison of ERP and RT

Similarly to the ERP analysis, the data for RTs were also averaged using a 15 trial moving window, thus allowing examination of the RTs propagation during the task. This provided continuous-like time series of RTs, together with the P3a and P3b amplitude and latency values, further enabling the observation of common trends between these two modalities of attention monitoring. In this way it was possible to examine the correlation between the values of the P3a and P3b amplitudes and RTs.

Statistical Analysis

In order to examine the difference of the GA ERPs between ‘go’ and ‘no-go’ condition, a paired t-test was performed. The ERPs used for ‘go/no-go’ comparison included all ERPs related to the ‘no-go’ condition and 50 ERPs related to ‘go’ stimuli preceding the 'no-go' condition. To identify latencies with significant difference of go and no-go stimuli, mean amplitude values of GA ERPs across subjects were extracted over fixed 20ms time windows. 'Windows of interest' were defined as follows: where successive bins achieved statistical significance, one after first, and one before last bin in this significant 'run' respectfully marked its beginning and ending. That is to say, times were treated as the windows of interest only if neighbouring 20ms bins were also significant ($p < .05$). After identification of these windows, mean amplitudes across the window were computed and further analysis was conducted. Due to multiple comparisons, Bonferoni corrections were applied where necessary and the reported pattern of data did not change.

The correlation between the values of the RTs and P3a and P3b peak amplitudes and latencies, were statistically analysed: vectors of P3a and P3b mean amplitude/latency values, calculated from the 435 values of the averaged 15 ERPs, and analogous values of the RTs were fed to SPSS and Pearson correlation coefficients were extracted.

Results

EEG Results

ERPs were successfully extracted confirming the validity of the setup and accurate synchronization of the stimuli-inferred marking of EEG stream. Figure 3 depicts GA ERPs for the go (full line) and no-go (dotted line) tasks for Fz, Cz, CPz and Pz electrode sites. The P3a and P3b values in the 'go' condition were significantly higher than in 'no-go' condition ($p< .05$), while the more prominent N2 component was elicited over 'no-go' trials ($p< .05$), as marked on the upper-left image of Figure 3. Further, the P300 peak elicited in our task was bifurcated, containing its both sub-components (P3a and

P3b), as shown on the upper-left image of Figure 3.

[Figure 3 near here]

The P3a and P3b components were consistent throughout the trials, which is represented in the colour maps, on the upper trace of Figure 4. (a, c, d and f), that represents an example of data obtained from subject 11 (Table 1). The lower traces of Figure 4 (a, c, d and f) represent the average ERP waveform on the single subject level, which confirmed that our task paradigm was suitable for electing the P3a and P3b ERP waveforms for ‘go’ conditions in simulated workplace environment. Additionally, Figure 4b and 4e represent the topographic maps and the distribution of the P3a and P3b sub-components across the scalp locations.

[Figure 4 near here]

Finally, the time series of the 435-averaged P3b components' mean amplitudes (upper panel of the Figure 5) and the corresponding averaged time series of the RTs (lower panel of the Figure 5) are presented for the visualization of the effect of variation of the P3b ERP component and RTs. Vertical full lines indicate moments when P3b mean amplitude starts dropping, eventually reaching its lower peak (depicted with dashed lines). Red arrows on the top of the Figure 5 represent the direction of the decrease in P300 amplitude. It is notable that when the P3b amplitude is decreasing, opposite trend in RT can be observed.

[Figure 5 near here]

Errors of Commission

There was only one participant who executed errors on the ‘no-go’ trials (six errors of commission, approximately 10% of all ‘no-go’ trials). Additionally, none of the participants committed errors of omission. Given that there were very few errors in total, we did not carried out further analysis regarding this matter.

Go-No-go Comparison

Paired sample t-test for the N2 ERP component at all four electrode sites revealed statistically significant difference between 'go' and 'no-go' trials (Fz: t(1,11)=3.42, p<.01; Cz: t(1,11)=3.26, p<.01; CPz: t(1,11)=3.40, p<.01; Pz: t(1,11)=3.31, p<.01). Similarly we observed statistically significant differences across 'go/no-go' trials at all four channels for P3a (Fz: t(1,11)=3.30, p<.01; Cz: t(1,11)=3.80, p<.01; CPz: t(1,11)=4.55, p<.001; Pz: t(1,11)=4.64, p<.001) as well as for P3b (Fz: t(1,11)=2.54, p<.05; Cz: t(1,11)=3.40, p<.01; CPz: t(1,11)=6.11, p<.001; Pz: t(1,11)=8.72, p<.001) ERP components.

Pearson's Correlation Results

In order to evaluate the correlation between ERPs and RTs we used Pearson correlation. To further examine the strength of obtained correlation results we also applied the Bootstrapping and Fisher-Z method on our data, verifying the consistence of the obtained results. The results of correlation between the RTs and P3a and P3b mean amplitudes are presented in the Table 1. These revealed that, on the group level, the correlation was negative on all electrode sites under study, with the high statistical significance (p< .001,Table 1).

[Table 1 near here]

However, compared to the group level, the overall significance of Pearson correlation varied substantially between individual participants at all four sites and in both P3a and P3b ERP windows. The results were less variable in the P3b compared to P3a window (values of correlation are presented in lower part of Table 1). Moreover, even in the P3b window, as obvious from the Table 1, only 4 out of 12 participants followed the general trend of negative correlation between ERPs and RTs at all four sites. Another four participants had significant negative correlations at 3, 2 or only 1 electrode site. Finally, one participant even had positive correlation over all sites, while the remaining three participants had positive correlations at 2 or 3 electrode-sites under study.

Unlike the mean P3a and P3b amplitudes, the correlation between RTs and P3a and P3b latencies was inconsistent. Moreover, the distribution of latencies at all four sites of interest (Fz, Cz, CPz and Pz), across both P3a and P3b windows significantly differed from normal distribution. For that reason, the log instead of raw values was used, which approximated normal distribution somewhat better. At the group level, the P3b sub-component showed only two marginally significant negative correlations (at CPz and Pz electrode sites). On the other hand, P3a subcomponent latencies showed positive correlation at all electrode sites ($p<0.05$) at the group level. However, when analysed for the individual subjects, the pattern of results was inconclusive.

Based on the results reported beforehand, we identified two groups of participants, five participants who showed negative correlation between RTs and P3b amplitude in one group, and four who showed positive correlation in the other. Regarding RTs, participants with negative correlation between RTs and P3b were faster ($t(RT)=2.2$, $p<.05$), with higher P3b amplitudes ($t(Fz)=35.21, p<.001$; $t(Cz)=38.91, p<.001$; $t(CPz)=39.68, p<.001$; $t(Pz)=28.36, p<.001$) and shorter P3b latencies ($t(Fz)=36.31, p<.001$; $t(Cz)=30.74, p<.001$; $t(CPz)=30.43, p<.001$; $t(Pz)=34.61, p<.001$). On the other hand, the positively correlated participants showed slower RTs, lower P3b amplitudes and longer latencies.

Similarly, with regard to P3a component, two groups of participants (four in each) demonstrated the same pattern of results. Negatively correlated had higher amplitude ($t(Fz)=22.2, p<.001$; $t(Cz)=26.5, p<.001$; $t(CPz)=27.14, p<.001$; $t(Pz)=16.84, p<.001$) and shorter latencies ($t(Fz)=18.77, p<.001$; $t(Cz)=11.05, p<.001$; $t(CPz)=7.51, p<.001$;

t(Pz)=9.89,p<.001), and vice versa for positively correlated. However, there were no significant group differences regarding RTs.

Discussion

The grand average comparison between ERPs extracted for 'go' and 'no-go' stimuli revealed that the higher P300 amplitude values are elicited for frequent 'go' condition. This is in contrast to most of the other findings, where participants were required to respond to deviant (infrequent) stimuli. However, this manipulation (with responding to frequent stimuli) was necessary, given that the study was conducted in simulated working environment, whereby the continuity of operation is essential. Therefore, the lower amplitude value of the 'no-go' P300 component is not surprising (Figure 3), since the passive stimulus processing generally produces reduced P300 amplitudes, as non-task events engage attention resources to reduce the amplitude (Polich 2007).

The Pearson's correlation between the RTs and P3a and P3b amplitudes, on the group level at all four sites of interest, showed significant negative correlation (Table 1). This confirms our main hypothesis, proving that the higher P300 amplitude values, which reflect the higher level of attention allocated to the task (Hohnsbein, Falkenstein, and Hoormann 1998; Murata, Uetake, and Takasawa 2005) correspond to the shorter RTs needed to complete the action. Additionally, higher values of negative correlation were obtained for the P3b, compared to P3a sub-component. However, the correlations between these modalities on the individual level were not consistent as within the group (Table 1), which constitutes one of the main finding of this study. This inconsistency could be attributed to the inter-individual differences, as the P300 component is influenced with the various factors, e.g. intelligence, introversion/extraversion, etc. (Picton 1992), but there can be also individual differences that are not functional but anatomical, such as scull thickness (Hagemann et al. 2008). Furthermore, the RT variability is also known to be subjected to inter-individual differences (MacDonald, Nyberg, and Bäckman 2007). Therefore, we support the notion of Hockey et al. (2009), where the importance of studying individual level data when performing psychophysiological measurements in ergonomics studies was emphasized.

Based on the Pearson's correlations between RT and P3b we identified two groups of participants, one of which was negatively correlated and the other one positively correlated. Negatively correlated group was faster with higher P3b amplitudes and shorter P3b latencies, whereby the positively correlated group showed slower RTs, lower amplitudes and longer latencies. Similar pattern of the results was observed for the P3a component (except for the RT comparisons, which were not significant). Therefore, it may be concluded that participants who showed negative correlation between P3b component and RTs were more focused on the task (given that they had higher P3b amplitude values) and were more efficient (given shorter RTs) than the positively correlated group. However, this finding should be examined in future studies and the consistency of the correlation results on individual basis needs to be confirmed through repeated measures on a single subject basis.

Another interesting comparison would be between ERPs on 'go' trials preceding correctly withhold 'no-go' trials and on 'go' trials preceding commission error on 'no-go' trials, as this could be an useful information on alerting the attention system (Robertson et al. 1997). However, the fact is that there was only one participant who executed actions on 'no-go' trials (6 errors in total, app. 10%). Interestingly enough, this was the participant (No.12, from Table 1) who showed a positive correlation between RTs and P3 amplitudes, in contrast to the generally observed trend (negative correlation between RTs and P3 amplitudes). It is noteworthy that it was hard to set an objective criterion as to what action to mark as an error, given that participants would sometimes demonstrate slight movements without executing the action. Therefore, we chose the stricter criterion based on which the errors of commission were defined as completion of the action on 'no-go' trials (including the pedal press).

Although the P300 component is generally related to attention processing, the mechanisms that generate P3a and P3b subcomponents differ significantly. P3a component is more related to novelty preference, processing of exogenous aspects of stimuli, i.e. low-level attention processes (Daffner et al. 2000; Polich 2007). This component usually follows the N2 component, which was also found to be increased in response to novel or deviant stimuli processing (Daffner et al. 2000), as also shown on Figure 3.On the other hand, P3b component was found to be more related to high-level attention processing, processing of endogenous aspects of stimuli, context-updating information (working memory) and memory storage (Polich 2007). The P3b component is also related to decision processes (O'Connell et al. 2012), in which it mediates function between stimulus processing and required response (Verleger et al. 2005). This is in line with our findings, since the P3b was more prominent in response to go-stimuli, which required action, particularly in central and centro-parietal sites.

We further examined the continuous-like time series of the RTs and P3a and P3b amplitudes and we noted the visible trends of fluctuation of these two modalities over time (Figure 5). Existing literature suggests that both RTs (Flehming et al. 2007) and P300 component (especially P3b, Polich et al. [2007]) are closely related to the attention, thus we can infer that fluctuation of these modalities correspond to the attention fluctuation on the neural as well as on the behavioural level. However, it is apparent from our results that not all the participants showed negative correlation between RTs and P3a and P3bcomponents, which arises an obvious question: which data are more closely related to the attention and should ERP or RT measures be used for evaluation of the assembler attention? Bishu and Drury (1988) pointed out that in assembly tasks translational stage from input information into output action is more complex than in conventional RT tasks and therefore, the structure of the response may influence the performance. Moreover, in RT experiments there are many possible processes that contribute to the RT and therefore it is difficult to isolate and address specific feature of interest, such as attention (Salthouse and Hedden 2002). On the other hand, the P3b component is found to be the direct correlate of the higher-level attention processing (Verleger, Jaśkowski, and Wascher 2005). Following this logic, we speculate that findings in this study demonstrate that ERP correlates of attention offer a more detailed and sophisticated understanding of the nature of attention decline compared to robust, but rough RT measures. Not only that we are able to achieve precision of measurement with ERPs (which is recognized as 'reaction time of the 21st century', Luck, Woodman, and Vogel [2000]), but also gain more insightful understanding of the nature of the process as demonstrated through the analysis of P3a and P3b sub-components. However, further studies are desirable to confirm the generality of this finding.

The analysis of the relationship between RTs and P3a and P3b peak latencies, revealed no statistically significant correlations between these components. Although Murata, Uetake, and Takasawa (2005) proposed that the P300 peak latency corresponds to the stimulus evaluation time and that it can be also directly correlated to the level of attention, this was not observed in our study. This finding is consistent with the recent work of Ramchurn et al. (2014) and it confirms that only the P300 component amplitude variation, but not its latency, correlates with the variation of the RTs. The P300 amplitude, on the other hand, was recognized as an index of the attention allocated to the task in numerous studies (Polich 1988; Murata, Uetake, and Takasawa 2005; Polich 2007; De Vos, Gandras, and Debener 2014 and Ramchurn et al. 2014).

It was reported that the sudden drops in the attention, during a monotonous task, could be attributed to the e.g., daydreaming and mind wandering (Fisher, 1998). However, the neural correlates of these phenomena are still not fully understood (Hasenkamp et al., 2012). For instance, potential benefit of real-time attention monitoring, would be to provide the feedback to the operator once the attention level starts decreasing, thereby attempting to keep the attention level high and prevent possible human errors. The presented study indicates that "periods of attention oscillation" are sufficiently long to make such a feedback system meaningful. However, one of the limitations of the present study is that the results were obtained in an off-line analysis. Therefore, one of the directions of future studies will be utilization of one of the existing Brain Computer Interface (BCI) software packages for real-time data processing in the desired time window and to provide proper visual, auditory or mechanical (e.g. vibration) feedback. The process could be automated in sense that once the amplitude values of the P3b component start decreasing with an obvious trend, as indicated by red arrows on Fig 5. (e.g. between 180th and 200th averaged trial), the feedback could be provided. It is important to investigate the effects of such a feedback also in relation with its content, all the while taking care of workers privacy and mental well-being.

Although, the authors believe that the measurement of covert attention-related modality (P3b) offers better understanding of attention processes than the overt performance measure of RTs, one of the limitations of present study is that EEG is still uncomfortable for everyday use and on-site recordings in naturalistic industrial environments. The main reason for this is that the reliable EEG recordings still depends on the wet gel-based electrodes (Mihajlovic et al. 2015) and an ethical question of EEG recording arises, in sense that the supervisor could have information about the physiological signals obtained from employees, raising privacy concerns (Fairclough 2014). Nevertheless, if the positive/negative correlation between P3b component's amplitude and RTs is holds on a single subject basis, then proposed methodology can be applied as that a primary (entry) test for workers. The benefits of such a testing can be twofold: firstly, the company management could be able to early detect whether the worker, for particular work position, is focused on the task (based on which group he belongs - positively/negatively correlated); secondly, the reliable, comfortable and low-cost attention-monitoring system could be created based solely on non-invasive RTs recordings. Thus, the future studies should be directed towards investigation of the reliability of correlation between P3b and RTs on single subject basis, upon which the proposed methodology could be applied in industrial settings.

The presented methodology was applied on a manual assembly work, where a single functional modification of the real workplace was needed, in the sense of on-screen stimulus presentation for the aim of eliciting the anticipated P300 ERP component. This modification was necessary, since the covert cognitive context is usually encrypted in complex brain dynamics and in naturalistic settings it is hard to isolate the specific cognitive processes, since they should firstly be evoked (Bulling and Zander, 2014). Therefore, at current stage this methodology cannot be directly applied for the on-site recording in realistic industrial settings and other workplaces, as we would have had to modify the work routine. For that reason, either a more general approach needs to be developed for further application to this work position, or another work position has to be identified, where such attention monitoring systems can be readily applied. These represent an additional direction for future research in this area.

Conclusions

In this study, we extended existing psychophysiological approaches in ergonomics by providing novel methodology for workers' continuous attention monitoring, during the course of a monotonous assembly task and in the realistic workplace environment. We observed that, while on the group level P3a and P3b attention related ERP component amplitudes, and the RTs correlated in the negative fashion, that did not hold on individual subjects' level. This constitutes one of our major findings: overt performance measure of RTs alone are not reliable attention level measure *per se*, and covert physiological data also needs to be employed for this task. Oscillating attention justifies the use of future feedback systems that would serve both to increase the attentiveness of workers and to prevent work-related errors. In that way, the potential accidents, which could lead to workers injuries and material damage, could be prevented, consequently increasing the workers overall well-being. Future studies are still needed to confirm the applicability of proposed methods, as well as to tune and sufficiently generalize them.

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List of Figures and Tables:

Table 1. Pearson's correlation values between the RTs and P3a and P3b mean amplitudes on the group level (upper part) and on the individual level (lower part of the table).

Figure 1. Left image – Real workplace (replicated from our industrial partner); Right image – Replicated workplace. The numbered elements from the left image (1,2,3,4) represent the machine operational parts that were replicated in laboratory settings (1R, 2R, 3R, 4R). 1- the machine opening for the crimping operation; 2 – industrial lamps for identification of correct placement of the uncompleted parts (rubber hose and metal part); 3 – Display for the information presentation to the worker; 4 - industrial lightning for the workplace. The right image also shows boxes for placing of the rubber hoses (RH), metal parts (MP) and completed parts (CP).

Figure 2. Step by step representation of the simulated working process. Step 1 – Stimulus presentation; step 2 – taking the rubber hose; step 3 – taking the metal part; step 4 – placing metal part on the rubber hose; step 5 – insertion of the uncompleted part inside the improvised machine opening; step 6 – pressing the pedal in order to initiate

the simulated crimping operation; step 7 – placing the completed into the box with completed parts; step 8 – waiting for the successive stimulus presentation.

Figure 3. Grand average ERP waveform for 'go' (full line) and 'no-go' (dotted line) conditions across electrode sites under study. The N2, P3a and P3b ERP components are indicated on the upper left image.

Figure 4. The average ERP waveforms, from subject 11 (Table 1) and for 450 go trials (a, c, d, f – lower traces); P3a and P3b sub components of bifurcated P300 peak are indicated in the lower trace of image (a); the amplitudes were calculated for the window between the full lines for both P3a and P3b (as marked on images a, b, d, f). Further, the topography of P3a and P3b components are represented on images (b) and (e).

Figure 5: Visual representation of the time series of the 435-averaged P3b mean amplitude values (upper trace) versus 435-averaged RT values (lower trace).

Table 1. Pearson's correlation values between the RTs and P3a and P3b mean amplitudes on the group level (upper part) and on the individual level (lower part of the table).

Pearson's Correlation Values

Component	P3a				P3b			
Electrode site	Fz	Cz	CPz	Pz	Fz	Cz	CPz	Pz
Group level	-.23	-.16	-.15	-.03	-.24	-.25	-.27	-.18

Individual Subjects	P3a				P3b			
	Fz	Cz	CPz	Pz	Fz	Cz	CPz	Pz
1	-.04	-.01	.03	.07	-.27	-.26	-.23	-.18
2	-.16	-.13	-.05	-.05	-.14	-.18	-.19	-.20
3	-.14	.01	.09	.09	.12	.23	.18	.08
4	-.33	-.35	-.36	-.36	-.10	-.14	-.20	-.27
5	-.03	.02	.02	.03	-.19	-.15	-.11	-.06
6	-.05	-.03	-.03	-.02	-.15	-.10	-.07	-.04
7	.22	.22	.16	.14	.15	.23	.22	.19
8	-.18	-.07	-.03	-.01	-.18	-.07	-.05	-.08
9	.03	.19	.13	.10	.17	.17	.02	-.05
10	-.07	.13	.16	.16	-.01	-.14	.02	.06
11	-.53	-.60	-.61	-.52	-.46	-.46	-.46	-.40
12	.36	.44	.41	.36	.15	.12	.02	.19

▓ - Negative correlations (p<0.05)

░ - Positive Correlations (p<0.05)

☐ - Non significant values (p>0.05)

Fig. 1

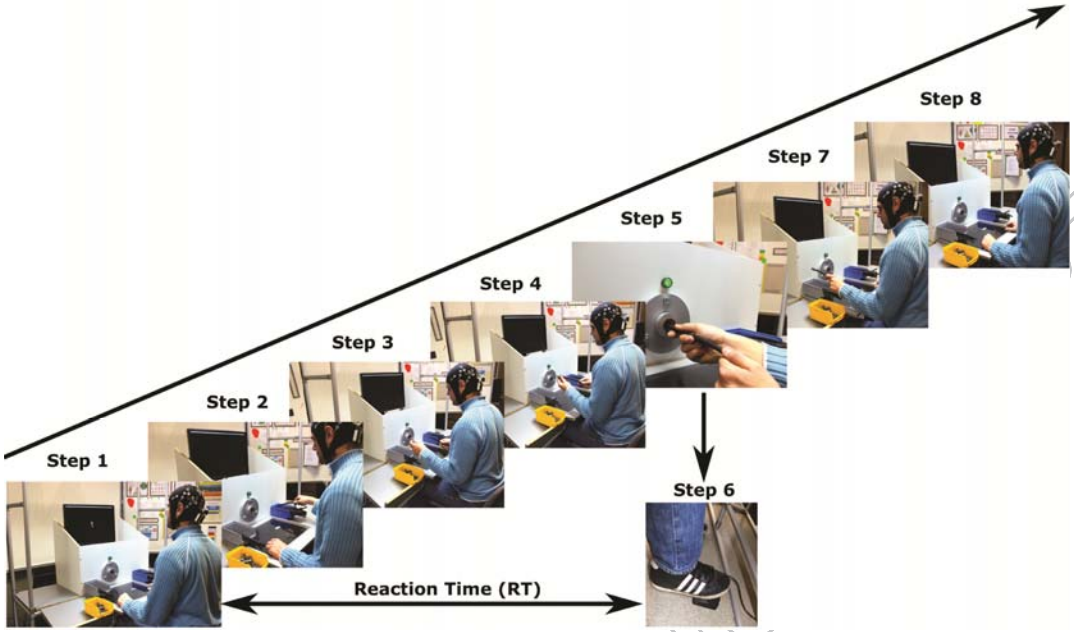
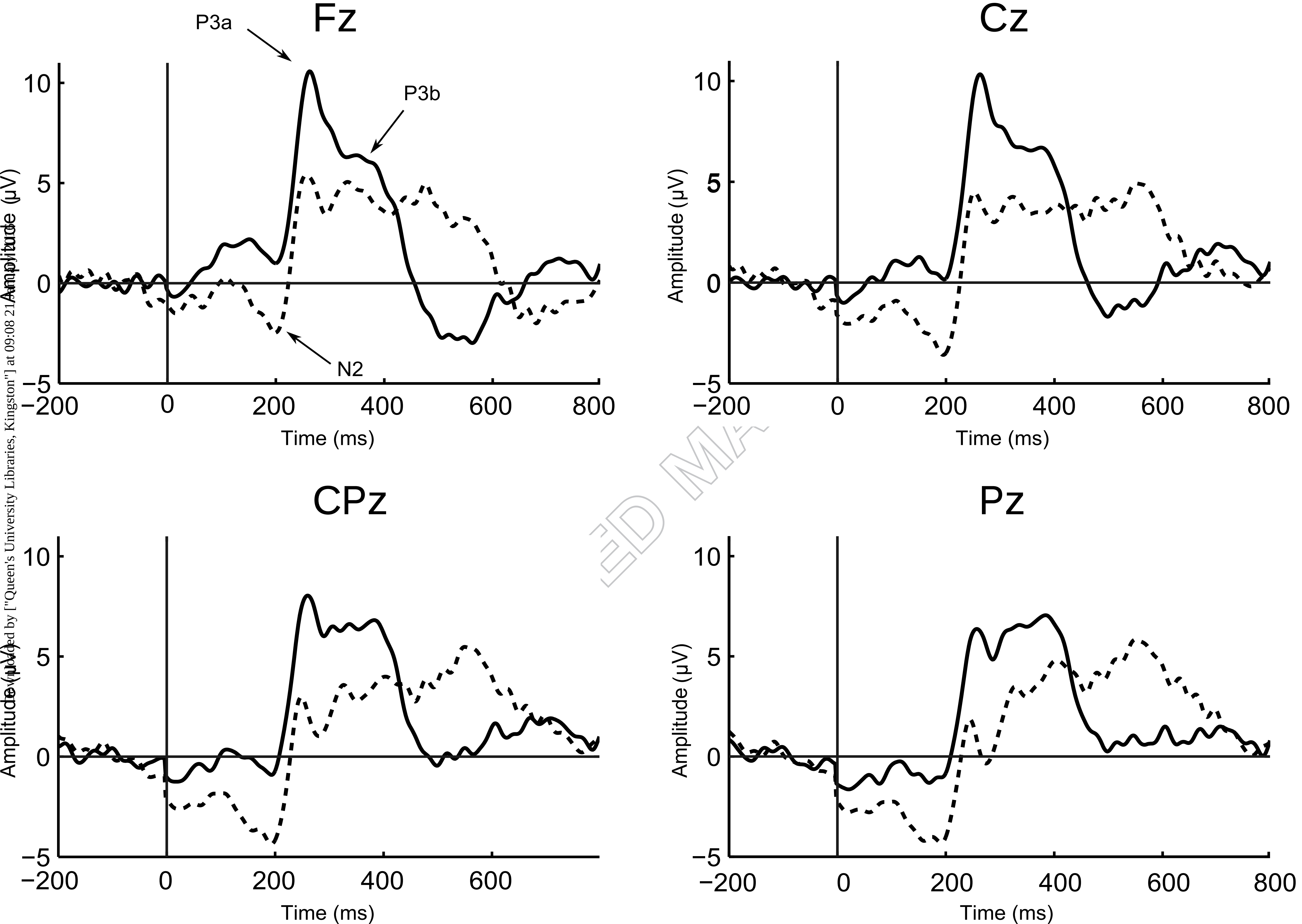
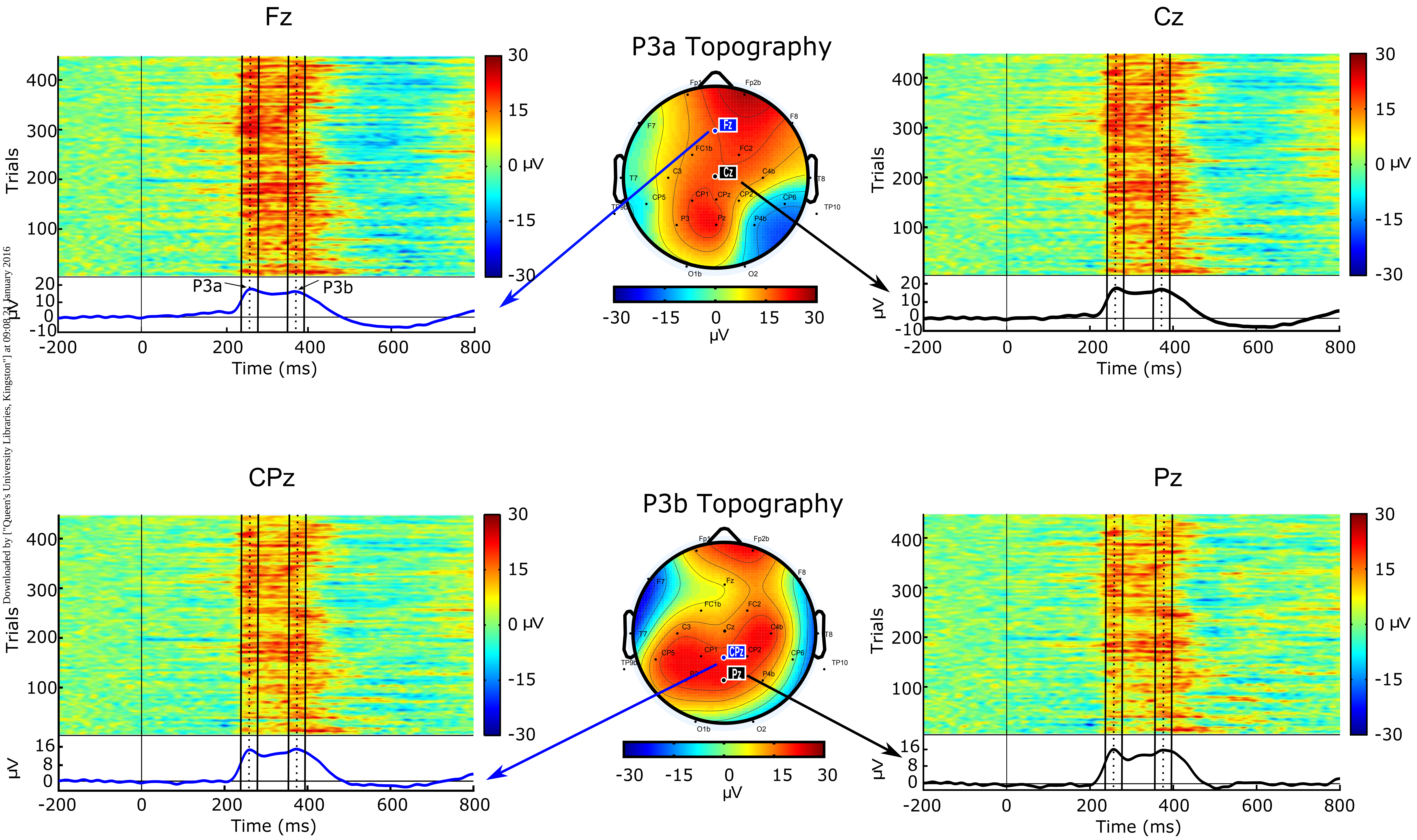
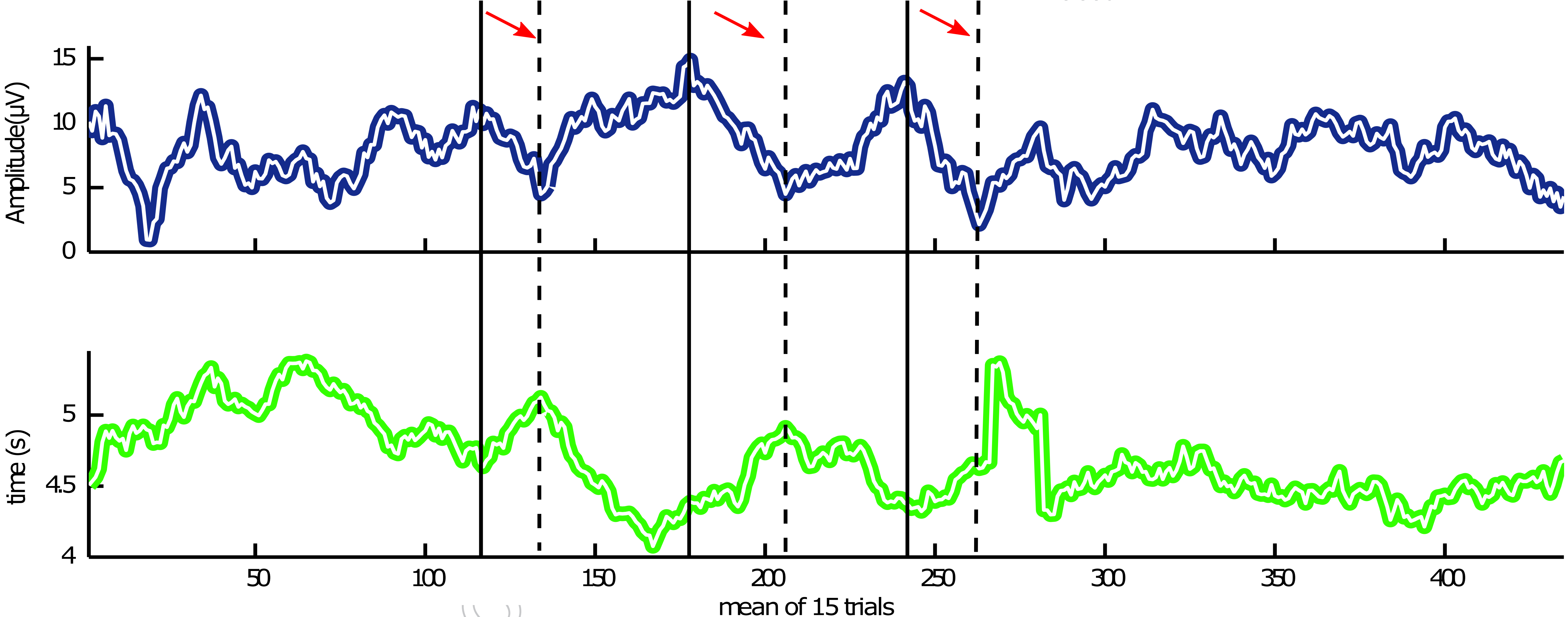

Step 1
Step 2
Step 3
Step 4
Step 5
Step 6
Step 7
Step 8
Reaction Time (RT)

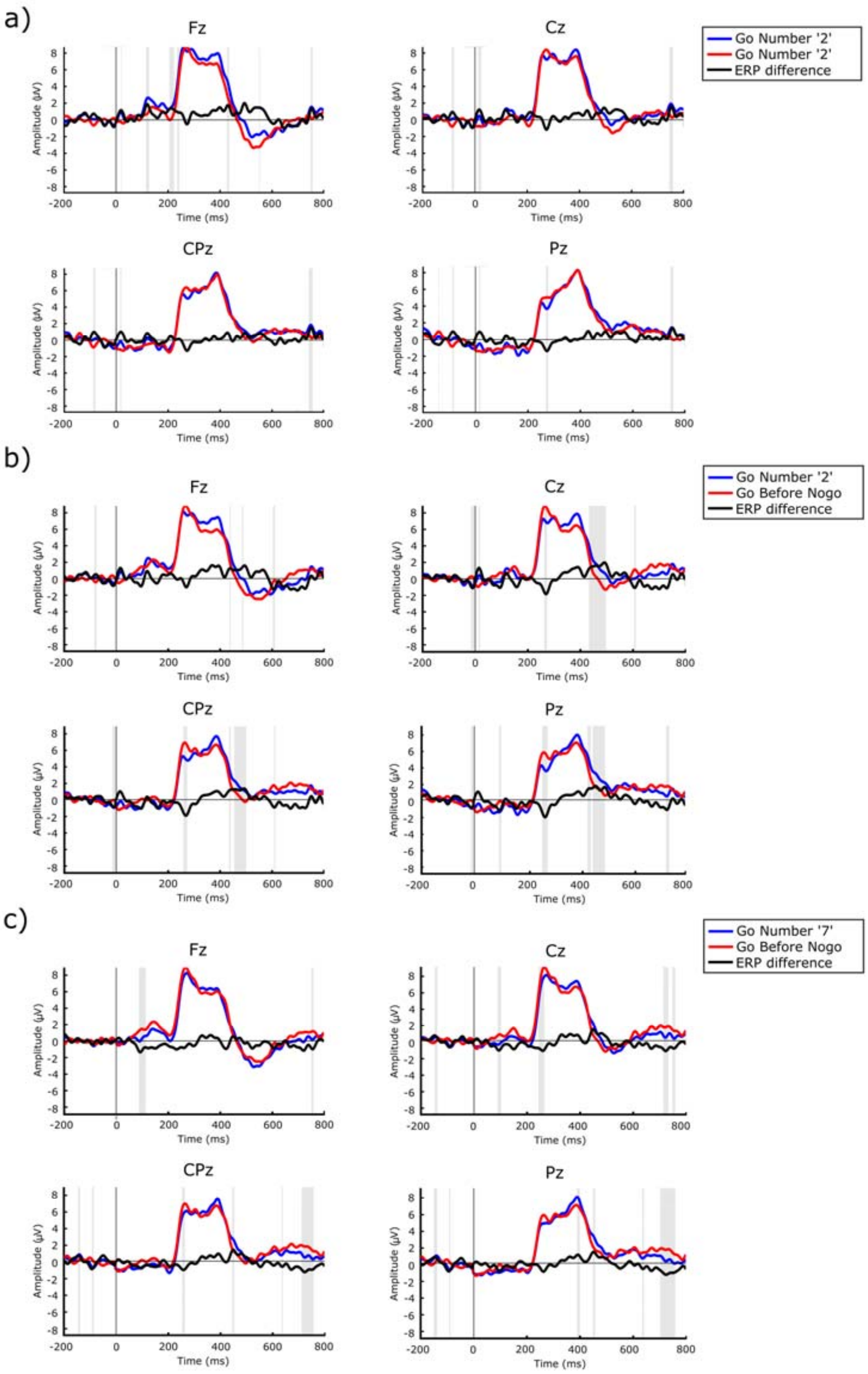
Fig. 2


Fz
P3a
P3b
N2
Amplitude (µV)
10
5
0
−5
−200
0
200
400
600
800
Time (ms)
Cz
Amplitude (µV)
10
5
0
−5
−200
0
200
400
600
800
Time (ms)
CPz
Amplitude (µV)
10
5
0
−5
−200
0
200
400
600
Time (ms)
Pz
Amplitude (µV)
10
5
0
−5
−200
0
200
400
600
800
Time (ms)

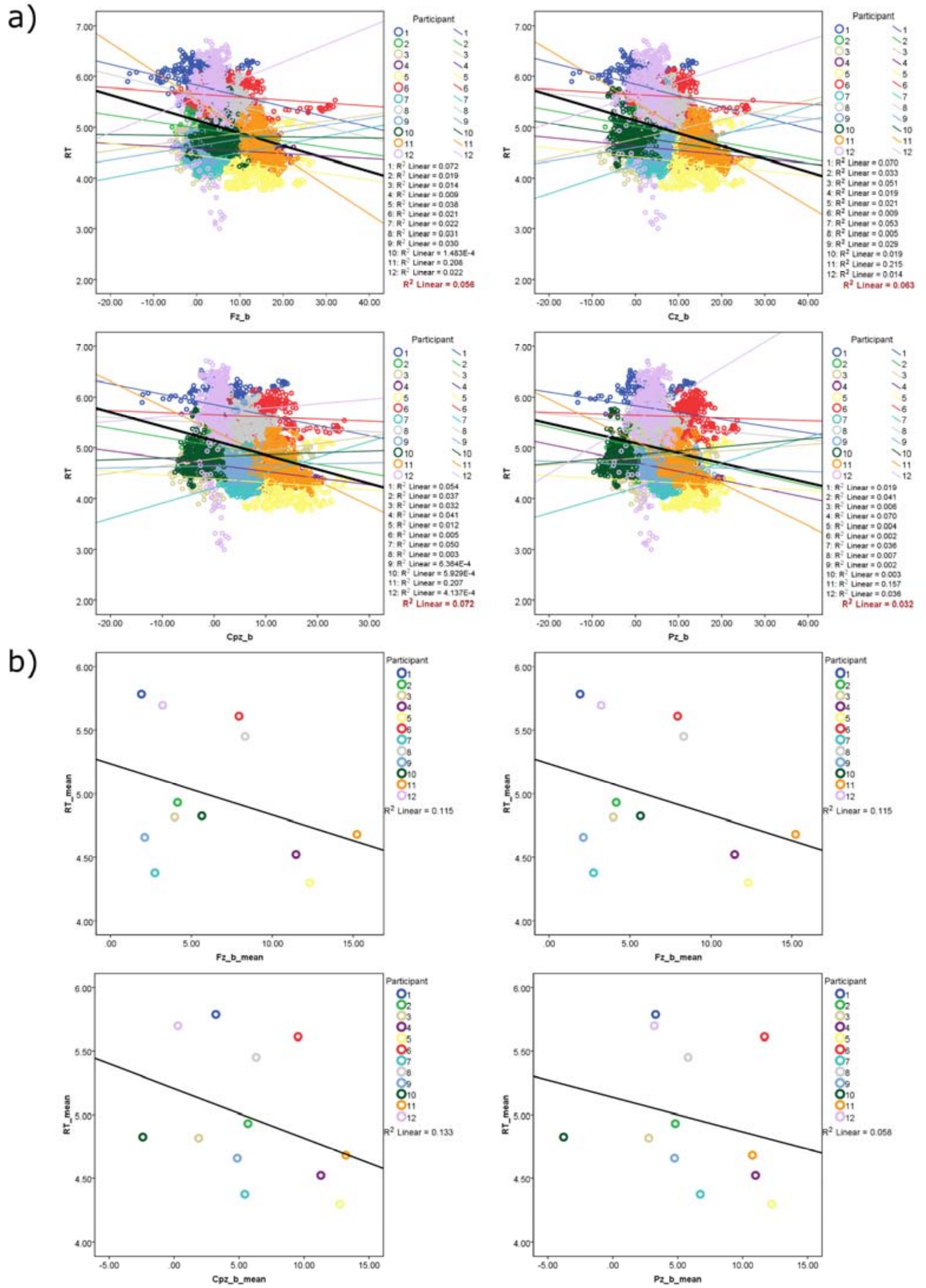

Fz
Cz
CPz
Pz
P3a Topography
P3b Topography
Trials
μV
Time (ms)
P3a
P3b
0 μV
30
15
-15
-30
-200
0
200
400
600
800
100
300
20
10
-10
16
8
Fp1
Fp2b
F7
F8
Fz
FC1b
FC2
C3
Cz
C4b
T7
T8
TP9b
TP10
CP5
CP1
CPz
CP2
CP6
P3
Pz
P4b
O1b
O2



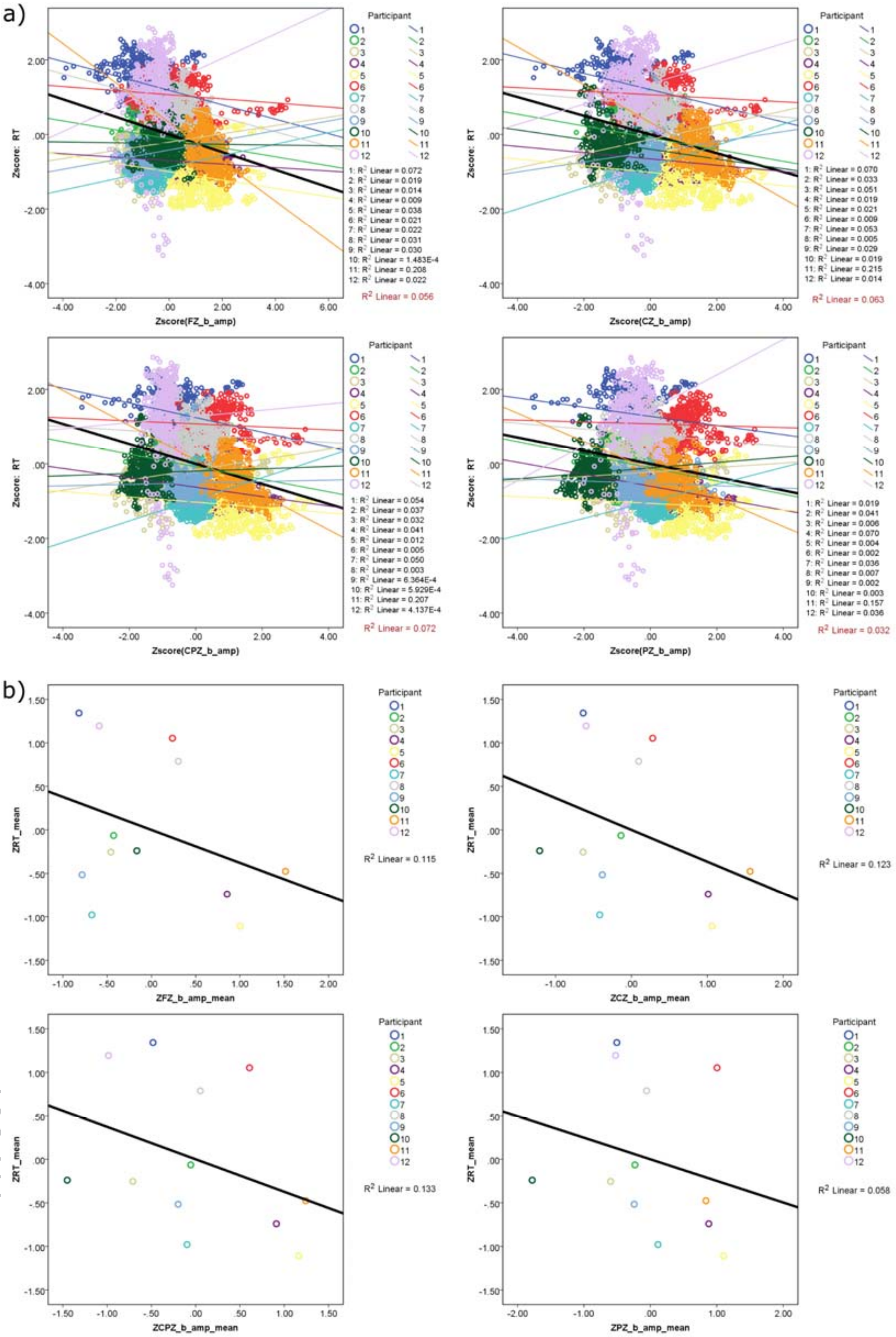
Amplitude(μV)
15
10
5
0
time (s)
5
4.5
4
50
100
150
200
250
300
350
400
mean of 15 trials



Supplementary Figure 1



Supplementary Figure 2


a)
Zscore: RT
Zscore(FZ_b_amp)
Participant
1
2
3
4
5
6
7
8
9
10
11
12
1: R² Linear = 0.072
2: R² Linear = 0.019
3: R² Linear = 0.014
4: R² Linear = 0.009
5: R² Linear = 0.038
6: R² Linear = 0.021
7: R² Linear = 0.022
8: R² Linear = 0.031
9: R² Linear = 0.030
10: R² Linear = 1.483E-4
11: R² Linear = 0.208
12: R² Linear = 0.022
R² Linear = 0.056
-4.00
-2.00
.00
2.00
4.00
6.00
Zscore(CZ_b_amp)
1: R² Linear = 0.070
2: R² Linear = 0.033
3: R² Linear = 0.051
4: R² Linear = 0.019
5: R² Linear = 0.021
6: R² Linear = 0.009
7: R² Linear = 0.053
8: R² Linear = 0.005
9: R² Linear = 0.029
10: R² Linear = 0.019
11: R² Linear = 0.215
12: R² Linear = 0.014
R² Linear = 0.063
Zscore(CPZ_b_amp)
1: R² Linear = 0.054
2: R² Linear = 0.037
3: R² Linear = 0.032
4: R² Linear = 0.041
5: R² Linear = 0.012
6: R² Linear = 0.005
7: R² Linear = 0.050
8: R² Linear = 0.003
9: R² Linear = 6.364E-4
10: R² Linear = 5.929E-4
11: R² Linear = 0.207
12: R² Linear = 4.137E-4
R² Linear = 0.072
Zscore(PZ_b_amp)
1: R² Linear = 0.019
2: R² Linear = 0.041
3: R² Linear = 0.006
4: R² Linear = 0.070
5: R² Linear = 0.004
6: R² Linear = 0.002
7: R² Linear = 0.036
8: R² Linear = 0.007
9: R² Linear = 0.002
10: R² Linear = 0.003
11: R² Linear = 0.157
12: R² Linear = 0.036
R² Linear = 0.032
b)
ZRT_mean
1.50
1.00
.50
.00
-.50
-1.00
-1.50
ZFZ_b_amp_mean
R² Linear = 0.115
ZCZ_b_amp_mean
R² Linear = 0.123
ZCPZ_b_amp_mean
R² Linear = 0.133
ZPZ_b_amp_mean
R² Linear = 0.058