6-16-2016

The Impact of Latency Jitter on the Interpretation of P300 in the Assessment of Cognitive Function

Xiaoqian Yu
University of South Florida, xiaoqian@mail.usf.edu

The Impact of Latency Jitter on the Interpretation of P300 in the Assessment of Cognitive Function

by

Xiaoqian Yu

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Arts
Department of Psychology
College of Arts and Sciences
University of South Florida

Major Professor: Emanuel Donchin, Ph.D.
Chad Dubé, Ph.D.
Kristen Salomon, Ph.D.

Date of Approval:
June 15, 2016

Keywords: event-related potential, principal component analysis, PCA Woody

Table of Contents

List of Tables

List of Figures

Abstract

When stimuli processing time varies in an oddball paradigm, the latency of the P300 will vary across trials. In an oddball task requiring difficult response selections, as the variation of stimuli processing time increases, so does the variation of the P300 latency, causing latency jitters in the measurement. Averaging the P300 across different trials without adjusting this latency jitter will lead to diminished P300 amplitude, resulting in inaccurate conclusions from the data. Verleger et al. (2014) reported a diminished P300 amplitude in a difficult oddball task that required subjects to make response selections among stimuli that are difficult to distinguish, but his work did not correct for any latency jitter observed within his sample. The current study replicated the easy and hard oddball tasks conducted in Verleger et al.. Raw ERPs obtained from 16 subjects indicated a successful replication of the study. An examination of the behavioral data showed that there was substantial variation in the P300 during the hard oddball tasks, and a latency jitter correction was applied in the analysis. Results indicated that there was a significant increase in the amplitude of P300 after latency jitter correction, and that this P300 amplitude did not differ significantly between easy and hard oddball tasks. These results suggest that difficult decision requirement does not reduce the amplitude of the P300, and that latency jitter should be accounted for when analyzing data from tasks involving a difficult decision requirement.

.

The Impact of Latency Jitter on the Interpretation of P300 in the Assessment of Cognitive Function

Original study and its rationale

The oddball tasks in Verleger et al. (2014) are different from usual oddball tasks, each of the stimuli in these tasks has two dimensions: letter and frame color. Each stimulus consists of a letter (either X or U) surrounding by a frame in either blue or yellow (an outline of the task paradigm and its sample trials are shown in Figure 1). The frequency of the frequent stimuli and the rare stimuli in the oddball tasks is 80% and 20% respectively. In the 80/20 task, only one dimension needs to be taken into account in making a response selection, i.e., when letters were the 80/20 feature, subjects could ignore the frames and responded basing on letters. Thus it will be referred to as “easy oddball task” throughout the article. In the combination task, both dimensions (letter and frame color) must be taken into consideration. Response selections had to be made according to specific combinations of letter and frame color, i.e., when letters were the 80/20 feature, blue X (40%) and yellow U (10%) required a key 1 press with left hand, and yellow X (40%) and blue U (10%) required a key 4 press with right hand; when the color of the frame was the 80/20 feature, blue X (40%) and yellow U (10%) required a key 1 press with left hand, and blue U (40%) and yellow X (10%) required a key 4 press with right hand. This task will be referred to as “hard oddball task” in this paper.

Verleger et al. (2014) reported that the amplitude of the P300 is reduced in the hard oddball tasks since response selection becomes difficult. Further examination of the data suggests that a diminished P300 may not reflect the results accurately, but rather could be the result of several factors. First, since two dimensions (letter and frame color) of the stimulus have to be considered in order to make the correct response, as shown in previous studies (Kutas, McCarthy, & Donchin, 1977; Jongsma, Quiroga, & Rijn, 2003; Spencer, Abad, & Donchin, 2000), this difficult decision requirement is very likely to cause substantial latency jitters in the original experiments conducted by Verleger and colleagues. Averaging across trials without adjusting for latency jitter would result in diminished P300 amplitudes. In addition, error trials were not excluded from the data analysis, which could cause an overlapping component problem. Negative components such as error-related negativity (ERN) and feedback related negativity (FRN), both elicited when either errors are made or following a negative feedback, could contribute to a smaller observed P300.

Hypotheses on P300

Several hypotheses about the P300 have been proposed (see Polich, 2007 for a recent review). One line is centering on the concept of "template updating" such that the P300 is thought to be a neural index of updating an existing mental schema (Gonsalvez, Barry, Rushby, & Polich, 2007; Steiner, Brennan, Gonsalvez, & Barry, 2013). One of the most influential template updating theories is the context updating hypothesis (Donchin, 1981; Donchin & Coles, 1988). This hypothesis proposed that the P300 indicates the updating of current neural representations and, as such can be observed in an oddball paradigm. In these paradigms, which often have two stimuli with one is more frequent than the other. Stimuli that occur frequently form a relatively stable mental scheme, which termed the "context"; when a rare stimulus occurs, the "context" must "update" in order to represent the new stimuli within this new context (Coles and Rugg, 1995; Donchin et al., 1978; Kamp, Brumback, & Donchin, 2013; Pritchard, 1981). This updating of the context produces a neural response can be observed as the P300.

In addition, the amplitude of P300 is conversely related to the probability of the stimulus:, the lower the probability of the stimulus, the larger the resultant P300 amplitude. It has been previously reported that rare stimuli elicit the most robust P300 (Duncan-Johnson & Donchin, 1977; Picton, 1992). The context updating hypothesis suggests that, the P300 is involved in a stimulus evaluation process but is not involved in the decision making aspect. In this case, changing the response selection requirement should not alter P300 amplitude as long as the stimuli remain the same. Instead, rare stimuli in a hard oddball task should elicit P300 amplitudes similar to the ones in the easy oddball task.

Another possibility is that the P300 reflects an aspect of the decision making processes to different extents. One view proposes that the P300 is an index of decision making and that the amplitude of the P300 increases as decision making becomes more difficult due to the amount of effort is required (Kelly and O'Connell, 2013; O'Connell et al., 2012). Another view suggests that the P300 is related to both stimulus processing and response selection (Falkenstein, Hohnsbein, and Hoormann, 1994; Hillyard & Kutas, 1983; Kelly and O'Connell, 2013; Nieuwenhuis, Aston-Jones, and Cohen, 2005; O'Connell, Dockree, and Kelly, 2012; Rösler, Borgstedt, and Sojka, 1985; Verleger, Jas´kowski, and Wascher, 2005). To help understand this concept, a metaphorical statement was made in Verleger et al.'s (2015) that the P300 reflects the reactivation of the Stimulus-Response link (the S-R link), this metaphor was tested in Verleger and colleagues in 2014. In this view, the stronger the link between stimulus and response, the more robust the resulting P300 (Verleger, Schroll, and Hamker, 2013). Two premises needed to be met in order to produce the reactivation of this S-R link: (1) a S-R link should be built and

(2) this S-R link must not be activated for some time in order to be "reactivated". In other words, this link cannot be activated throughout the entire task duration. For instance, frequent stimuli builds a S-R link but the frequency of its occurrence does not allow for the required break for reactivation; in contrast, rare stimuli in an easy oddball task do not occur as frequently, so the S-R link is reactivated when a rare stimulus appears. In this case, the S-R link satisfies the two premises and a P300 would be elicited. According to this assumption, rare events in the hard oddball tasks, in which subjects must consider both frame color and letter in order to respond correctly, fail to meet the first criteria, as the decision making process impedes the development of the S-R link.

Potential factors contributing to diminished P300

Latency jitter

Several factors can alter the amplitude of the P300. First factor to be considered here is latency jitter. The latency of the P300 is the time period measured from the stimulus onset to the onset of the P300. Verleger (1997) view the P300 as an index of the decision making process (see also Verleger, Jas´kowski, & Wascher, 2005). In line with this view, other researchers have suggested that P300 latency indexes the duration of stimulus evaluation time (Donchin, 1981; Duncan-Johnson & Donchin, 1977; Magliero et al., 1984; Pritchard, 1981). If a task requires a difficult response judgement, the stimuli evaluation time will vary to a larger extent as a response decision is taking longer time to process. As a consequence, the latency of the P300 would vary substantially across trials, averaging across trials without controlling for the latency jitter would produce a diminished P300. Such variance in amplitude can be eliminated by applying latency jitter adjustment to the P300, as has been shown by Kutas et al. (1977) (see also McCarthy & Donchin, 1981).

Overlapping components

Overlapping components may also contribute to the diminished P300. In the original designs of both the easy oddball and hard oddball tasks, participants were neither given a description of the task nor instructed about the stimuli categorization before the study. Previous studies have indicated that this component does not affect the elicitation of the P300 (Ito & Cacioppo, 2000). During the task, if the correct key was pressed, subjects were allowed to continue and the next stimulus would be show. If an incorrect response was made, a blank screen with the grey background would stay on the screen until the correct key was pressed. This blank screen served as a feedback to participants' response indicating that the previous response selection was wrong. Feedback of this nature has been shown to elicit the feedback-related negativity (FRN), which peaks between 200 and 300 ms after feedback onset , in the centro-frontal area of the brain (Miltner, Braun, & Coles, 1997; Nieuwenhuis et al., 2004). Holroyd and Coles (2002) proposed that the FRN also indexes the activity of a reinforcement learning system to guide subsequent performance in the task.

Once had sufficient practice on the task, participants would have become aware of the correct key response to a stimulus. Under this circumstance, if a wrong key was pressed, another negative component known as the error-related negativity (ERN, or error negativity (Ne)) would be elicited in the centro-frontal area, peaking within 100 ms after an error response was made (Gehring, 1992; Gehring, Goss, Coles, Meyer, & Donchin, 1993). Unlike the generation of the FRN which requires a feedback of their performance, the ERN indexes the error monitoring system of the anterior cingulate cortex (ACC) (for a review, see Holroyd et al., 2004), and it occurs once an error comes to awareness. Although the ERN and the FRN have a similar distribution on the scalp in the centro-frontal area, their timing can still overlap with part of the

P300, resulting in a reduced positivity (Dehaene, Posner, & Tucker, 1994; Gehring, Himle, & Nisenson, 2000; Gehring and Willoughby, 2002; Van Veen and Carter, 2002; Yeung, Botvinick, & Cohen, 2004). In conclusion, the reduction in the raw ERPs reported by Verleger and colleagues is very likely not representing the data accurately.

Current study

The present study replicated the two oddball tasks of Experiment 1 in Verleger et al. (2014) and omitted the non-oddball control task since it is not relevant to the theme of this paper. Considering that the raw ERPs from Verleger et al. may not reflect the results accurately since Verleger and colleagues did not address either latency jitter problem or the concern of overlapping components. The current study intended to examine both behavioral data and event-related brain potentials (ERPs), latency jitter can be corrected by jitter correction techniques (Kutas, McCarthy, & Donchin, 1977; Spencer, Abad and Donchin, 2000), and overlapping components can be addressed by spatiotemporal Principal Component Analysis (PCA; Dien, Spencer & Donchin 2004). It was hypothesized that the amplitude of the P300 in the hard oddball tasks would increase to the similar extent as in the easy oddball tasks.

In the current study, different software from the original study was used, (1) stimuli presentation software: the psychology software tool: E-Prime 2.0 (Sharpsburg, PA) was used in lieu of Presentation software 14.5 to present the stimuli, record response selections, reaction time and send codes of the stimuli and response to another computer using to record EEG data. Other than the different software was used, the stimuli presentation strictly followed the design in the original study except the language: replacing German with English. (2) EEG processing software: EGI's Net station 5.2 software was used for EEG data acquisition and some analysis rather than Brain Analyzer software. (3) response equipment: the Serial Response Box was used to respond to the tasks instead of a standard keyboard since it features a 0 millisecond debounce period, while a standard keyboard can have various debounce periods. As a result, key 1 and key 4 were used for left and right hand press respectively in place of the two Ctrl keys on a standard keyboard in the original study. Other than the differences in software, the present study used 128-channel EGI Geodesic Sensor Net (EGI, Eugene, OR) to record the EEG data in replacement of the 64-channel net, the 128-channel net can provide more detailed spatio-temporal information of the ERP components.

	Stimuli		**Key Pressed** (1=Left Hand, 4=Right Hand)			
Percentage	**80% Letter**	**80% Color**	**Easy Oddball**		**Hard Oddball**	
			80%Letter	**80%Color**	**80%Letter**	**80%Color**
40%	x	x	1	1	1	4
40%	x	u	1	1	4	1
10%	u	x	4	4	4	1
10%	u	u	4	4	1	4

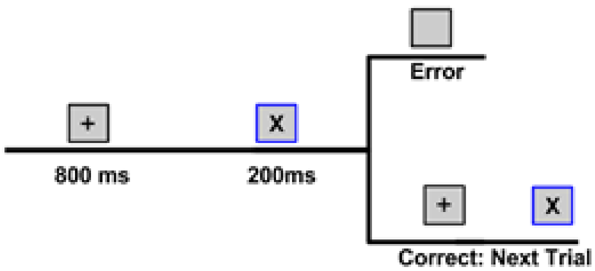


Figure 1. Outline of the task paradigm and sample trials. The easy oddball task was performed twice: once with frequent left-hand responses and once with frequent right-hand responses.

Method

Participants

Same as the original study, data were collected from 16 undergraduate students (12 female, mean = 19.63 years, SD = 2.58). The participants were recruited via Sona Systems, an online study registration system operated by the Department of Psychology at the University of South Florida. Participants were English speakers, with normal or corrected-to-normal vision, and had no neurological conditions. Only right-handed individuals were kept for the ERP analysis in order to reduce variances in the data (Willems, Van der Haegen, Fisher, & Francks, 2014). They received four course credits as compensation for their participation in the study.

Measures

Self-reported measures

Demographics Form. This form contains demographic information such as: age, gender, handedness, and family history of mental illness.

Stimuli and Tasks

As mentioned above, the easy oddball and hard oddball tasks were created in the psychology software tool: E-Prime 2.0 (Sharpsburg, PA). The parameters of the stimuli are in accordance with the design in Verleger et al.:

> In each trial, one of the two black letters X and U (Helvetica, 35 pt.) was presented for 200 ms at the center of a light gray 17″ screen, framed by a blue or yellow rectangle (2.3 cm × 2.5 cm width × height, line width 3 pixels). Each trial started with a small black

> fixation cross at screen center for 800 ms. Then, letter and frame were simultaneously presented for 200 ms. Pressing the correct key terminated the trial (i.e., when the incorrect key was pressed, the program waited for the correct press). There were 250 trials within each block. Thus, with average response times (RTs) of, for example, 400 ms and without any errors, blocks would last 250 trials × (800 + 400) ms = 300 s. (Verleger et al., 2014, p. 1091).

To respond, key 1 on the Serial Response Box needs to be pressed for frequent stimuli, and key 4 should be pressed for the rare stimuli. The key press makes the task difficult since the frequent and rare stimuli differ in different tasks.

In the 80/20 task, only one dimension needs to be taken into account. When letters were the 80/20 feature, subjects could ignore the frames and responded basing on letters. For example, 80% X required a key 1 press with left hand and U a key 4 press with right hand regardless of the frame color; Similar rules apply when frames were the 80/20 feature, subjects responded according to the color of the frames and letters can be ignored. In the hard oddball task, both dimensions needs to be taken into consideration. Response selections had to be made according to specific combinations of letter and frame color. Therefore, when letters were the 80/20 feature, blue X (40%) and yellow U (10%) required a key 1 press with left hand, and yellow X (40%) and blue U (10%) required a key 4 press with right hand. When the color of the frame was the 80/20 feature, blue X (40%) and yellow U (10%) required a key 1 press with left hand, and blue U (40%) and yellow X (10%) required a key 4 press with right hand. In addition, when subjects responded to the fixation (800 ms long) before seeing the stimulus, an error message would stay on the screen for 4 s in red 30 pt. font ("pressed too early," in English). All stimuli were displayed in E-Prime 2.0 with a grey background, response time, response selection were recorded in the log files imbedded in the software.

In order to balance the left-hand and right-hand responses, the assignment of key presses was reversed between blocks. That is, if the frequent stimuli required a key 1 press with left hand, then in the next block the frequent stimuli would require a key 4 press with right hand. Thus there were six blocks total in the computer task, two blocks in each of the three tasks: two hard oddball tasks, easy oddball left/right for colors and easy oddball left/right for letters.

Electroencephalographic (EEG) Acquisition

During the oddball tasks, EEG data was collected with 128-electrode EGI Geodesic Sensor Nets as opposed to 60-channel in the Verleger el al.'s (2014) study, allowing a more detailed investigation of the componential spatial characteristics. The data were sampled at 250 Hz, band pass filtered at 0.1 Hz and 25 Hz, and segmented into 1200 ms epochs: 200 ms before and 1000 ms after each stimulus. Each epoch was then processed in Net station in the following procedures: artifact rejection (i.e., eye movements and blinks, facial movements), bad channel replacement, averaging referenced and baselined corrected at 200 ms. Remaining clean data were sorted by frequent and rare stimuli in each task, then averaged across trails to generate the individual raw ERPs per task.

Procedure

Participants volunteered to take part in the study through the Psychology Department's research participant system Sona. Upon arriving in the lab, participants were given a consent form detailing the procedures of the study, the risks and benefits of participation. Once the form was carefully read and signed, participants were invited to the equipment room and the EEG net procedures would be applied by trained undergraduate research assistants. There were various sizes of nets, each net was chosen to fit the participants' head. After the EEG net was properly put on, the subject was taken to the test room with a computer screen and a Serial Response Box. All the 128 electrodes were tested for conductance using Net station, each electrode with an impedance lower than 50 Ω was considered in good conductance. After the usual preparations for the electroencephalographic (EEG) recording, participants were instructed to seat in a comfortable chair, which was about 1.2 meter in front of the experimental computer screen in the test room. The researchers then went to a control room separating from the test room by a one-way mirror, in order to monitor the EEG signal and the subjects' performance. Upon half-way into the study, the solution would be reapplied to the EEG net to ensure good conductance. At the end of the study, participants would receive a debriefing form and were given a chance to ask any questions relating to the study.

As described above, there were a total of six tasks, each block had 250 trials: 250*(800+400)ms=300 s, and subjects were allowed to take a 5-min break after each block to prevent constant eye blinks and increased muscle tensions during the tasks. The entire study lasted for about one hour, while the total in lab time was about two hours including reading the consent form session, filling out the demographic form, the preparation time of the EEG net solution, and the net application. The order of the six tasks was balanced across the 16 participants: half of the participants first had the three blocks of letter as the 80/20 feature, the other half had the three blocks of color as the 80/20 feature first. Within the three blocks, half of the subjects had the two easy oddball tasks first, and the other half had the hard oddball task first. Within these pairs of blocks, half of the subjects had the easy oddball tasks left/right first, while the other half had the easy oddball tasks right/left first.

Latency jitter correction

The Indicator of latency jitter

Fjell and colleagues (2008) proposed that reaction time (RT) and P300 latency covary. RT is measured as the time between stimulus presentation and the conclusion of the response. Within it, RT includes perception of the stimulus, response choice and response production (see also Luce, 1986, chap. 4). In the present study, left and right hand response was counterbalanced throughout the tasks, as a result, the motor activities for the response execution could be considered a constant variable. That is, RT is highly correlated with the stimulus evaluation duration, which is indexed by the P300 latency (Duncan-Johnson and Donchin, 1982; McCarthy & Donchin, 1981). The longer the time needed to evaluate the stimuli, the longer the reaction time. Hence, reaction time is a good indicator of latency jitter.

Since the mean RTs can not represent the changes in the RT entirely, the ex-Gaussian distribution was chosen to describe the change in RT more explicitly. The ex-Gaussian RT distribution model is a convolution of a Gaussian and an exponential distribution, its parameter mu (μ) corresponds to the mean of the normal distribution, sigma (σ) corresponds to the standard deviation of the normal distribution, and tau (τ) the mean and variance of the exponential distribution, referring to the extent of the right skewness of the RT distribution (Balota & Yap, 2011; Dawson, 1988; Heathcote et al. 1991; Hohle, 1965; Plourde & Besner, 1997; Spieler, Balota, & Faust, 1996; Hockley, 1982, 1984; Ratcliff, 1978, 1979). Heathcote et al. (1991) argued that ex-Gaussian fits are theory-neutral but these parameters provide more information about the characteristic of the RT than the standard approach to analyze mean RTs. The data was for assessed for outliers, and R studio was used to code the command to plot the ex-Gaussian RT distribution.

PCA Woody

PCA Woody is a method that was developed based on Woody filter (Woody, 1967), a type of signal detection technique used in ERP research (for a review, see Coles et al., 1986), and has been utilized to correct latency jitter in ERPs by several studies (Kutas, McCarthy, & Donchin, 1977; Spencer, Abad, & Donchin, 2000). The rationale of the Woody filter is that the ERPs in each trial is cross-correlated with the average ERP, the amount of latency jitter is assessed for each trial by looking for the maximal correlation between the trial and the average ERP. This information is used to shift the ERP wave for that trial. The concern of using Woody filter in the present study is that the waveforms to be analyzed are raw ERP waves, which may involve potential overlapping ERP components such as ERN and FRN as discussed above. In order to correct for latency jitter in the target component (the P300), the PCA Woody technique was adopted. Instead of using an average wave in the Woody filter procedure, PCA Woody uses a spatial factor as a template for the individual single-trial data, to slide across each epoch, the latency for each trial is then used for jitter correction. When using this procedure, principal component analysis (PCA) is firstly conducted to generate an initial spatial factor for each trial, then the spatial factor with a parietal scalp distribution (mostly likely to correspond to the P300) was used as the template for the single-trial data from each participant.

Principal Component Analysis (PCA)

A classical approach to disentangle overlapping components within an ERP is principal component analysis (PCA). Following the guidelines from Spencer et al. (1999), a spatiotemporal PCA procedure was applied to the dataset of 16 subjects' averaged files of 1,200 ms ERPs from 129 electrodes, separated by tasks. Spatial PCA was performed first then temporal PCA was then conducted on the obtained spatial PCA data using the most recent EP Toolkit developed by Joseph Dien, scree test (Cattell, 1966), which shows the number of factors to be retained and rotated suggested that 10 spatial factors were retained for each task. The temporal PCA was applied on each spatial factor independently. Three factors were retained (this step was also determined by the scree test), thus resulting in 30 spatio-temporal PCA. Promax rotations without Kaiser normalization were used to rotate both the spatial and temporal factors. Virtual ERPs were obtained by averaging the spatio-temporal of all participants in each task, which were further segmented into frequent and rare categories. Statistical analysis was performed using SPSS (17.0; SPSS, Inc., Chicago, Illinois, USA).

Results

Behavioral data

The current study's behavioral data were obtained from the log files in E-prime 2.0 as stated above, according to the criteria used in Verleger el al. (2014), reaction times (RTs) of correct responses between 150 ms and 1,000 ms after frame onset were kept for ERP analysis. Mean RTs and error rates are displayed in Figure 1. Responses were much slower, and more errors were committed in the hard oddball tasks compared to the easy oddball tasks, $F(1,15)=28.51$, $p<.001$ for RTs; $F(1,15)=54.41$, $p=0$ for error rates. Responses were much slower, and more errors were made with rare stimuli than with frequent stimuli, $F(1,15)= 8.08$, $p=0.012$ for RTs, $F(1,15)=73.32$, $p=0$ for error rates. There is a significant interaction effect of Task × Probability for error rate, $F(1,15)= 13.19$, $p=0.002$. Subjects were more likely to make a wrong response selection with rare stimuli than frequent stimuli in the hard oddball tasks.

ERP

All of the ERP data were adapted from Pz. Grand means of raw ERPs are displayed in Figure 3. ERP differences between rare and frequent waveforms are displayed in Figure 4. Letter and frame were presented simultaneously at time point 0 ms. Negative polarity is plotted upwards. The blue line and red line denote data in easy oddball task and hard oddball task respectively, then thin lines represent data from frequent events and thick lines represent data from rare events (frequent events are letter in the upper panel, and color in the lower panel). P300 was determined as mean amplitude between 200-500ms. There is a large P300 in easy oddball task, and a negligible one in the hard oddball task. A paired sample t-test was conducted to compare the P300 in the easy and hard oddball tasks. P300 in easy oddball (feature letter) task (M=2.90, SD=2.37) is significantly larger than in hard oddball task (M=1.71, SD=1.88), $t(15)=1.81$, $p<0.05$.

Ex-Gaussian RT distribution

The ex-Gaussian distribution of RT in each task and its parameters (mu, sigma, tau) were generated in Figure 5. Regardless of the 80/20 feature, the mu, sigma and tau are bigger in the hard oddball tasks than the easy oddball tasks.

Spatiotemporal Principal Component Analysis (PCA)

Following the guidelines from Spencer et al. (1999), a spatiotemporal PCA procedure was applied to the dataset of 16 subjects' averaged files to disentangle the overlapping components. Spatial PCA was performed first then temporal PCA. Using the most recent EP Toolkit developed by Joseph Dien, and based on the resulting Scree plot (Cattell, 1966), 10 spatial factors were retained for each task, accounted for at least 0.5% of the total variance and were retained for further analysis. Statistical analysis was performed using SPSS (17.0; SPSS, Inc., Chicago, Illinois, USA).

Variance for the ten spatial factor is displayed in Table 1. Variance of the retained spatial factors, spatial factor in parietal area, and spatial-temporal factors for P300 are shown in Table 2. Figure 6 shows the spatial factor loadings of easy oddball tasks, and pre/ post latency jitter correction for hard oddball tasks.

Virtual ERPs

Virtual ERPs from the spatiotemporal PCA are displayed in Figure 7. The amplitude of P300 for rare stimuli in the easy oddball task is significantly larger than that in hard oddball task when color is the 80% feature, $t(15)=-2.868$, $p<.05$. EP Toolkit was used to correct latency jitter, it uses a spatial PCA factor as a Woody filter template (Woody, 1967) to slide across the epoch, producing a cross-product fit statistic at each single-trial data, this information can then be used in the jitter-correct function to shift the single-trial data within a subject. After this procedure, the P300 amplitude in the hard oddball tasks is comparable to that in the easy oddball tasks (Figure 8), no statistical significance for either the P300 amplitude or the factor scores.

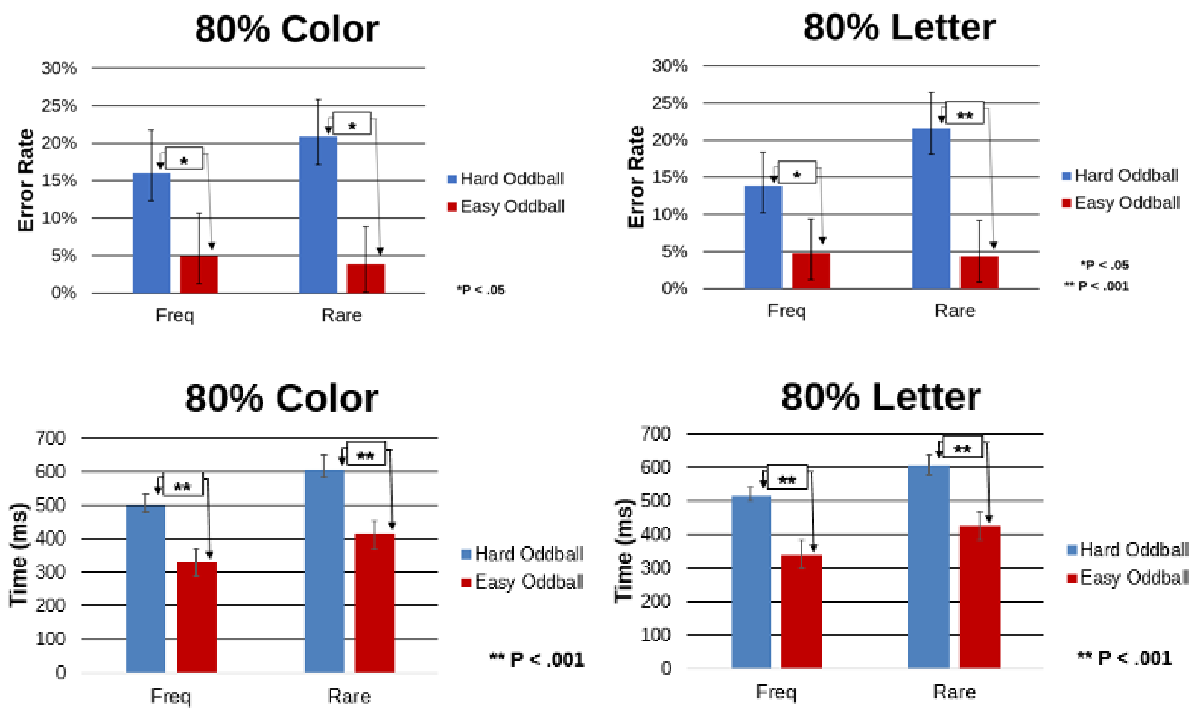


Figure 2. Error rate and reaction time for frequent and rare events in the easy and hard oddball tasks

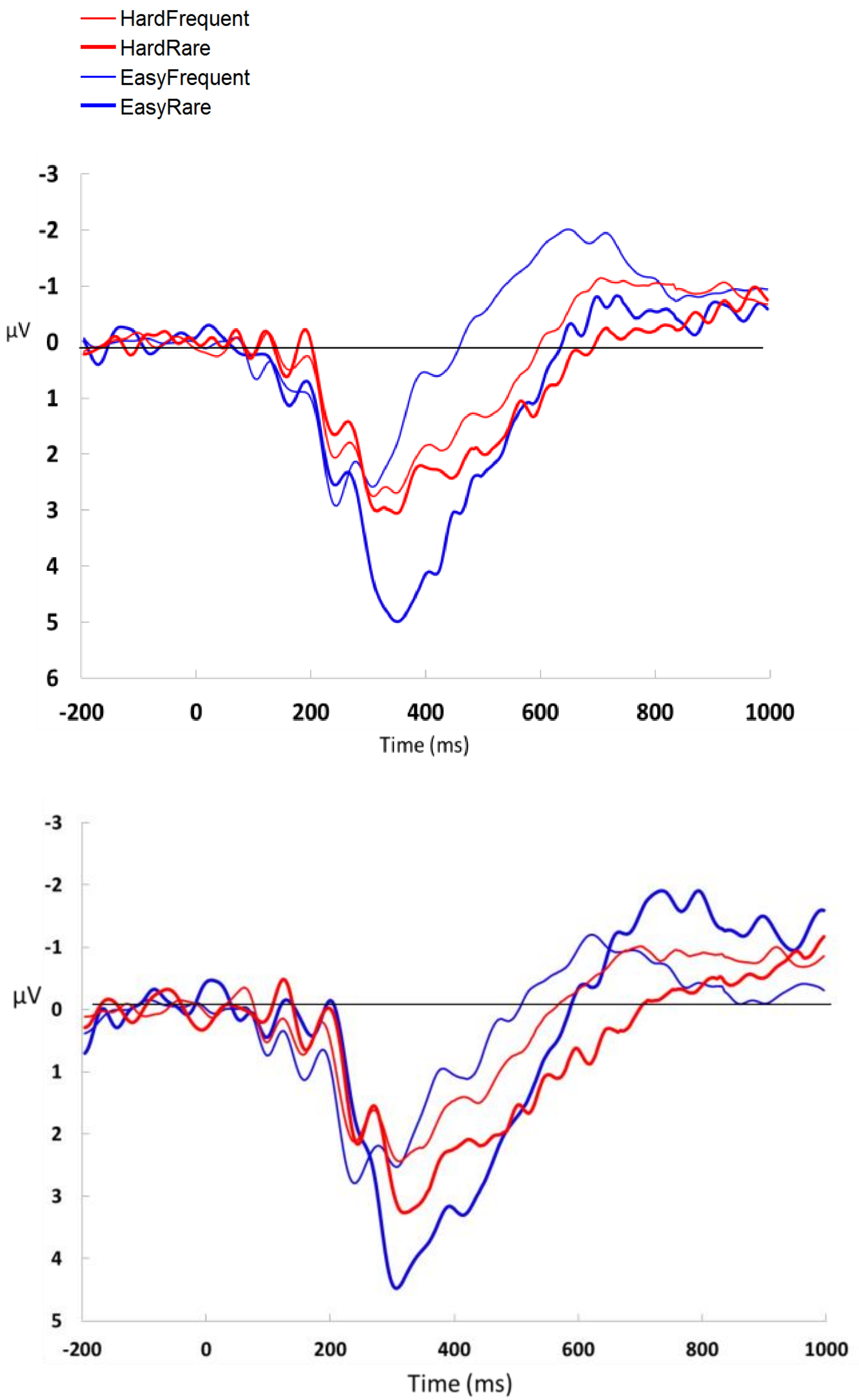


Figure 3. Grand average ERPs for easy and hard oddball tasks (80% letter left, 80% color right)

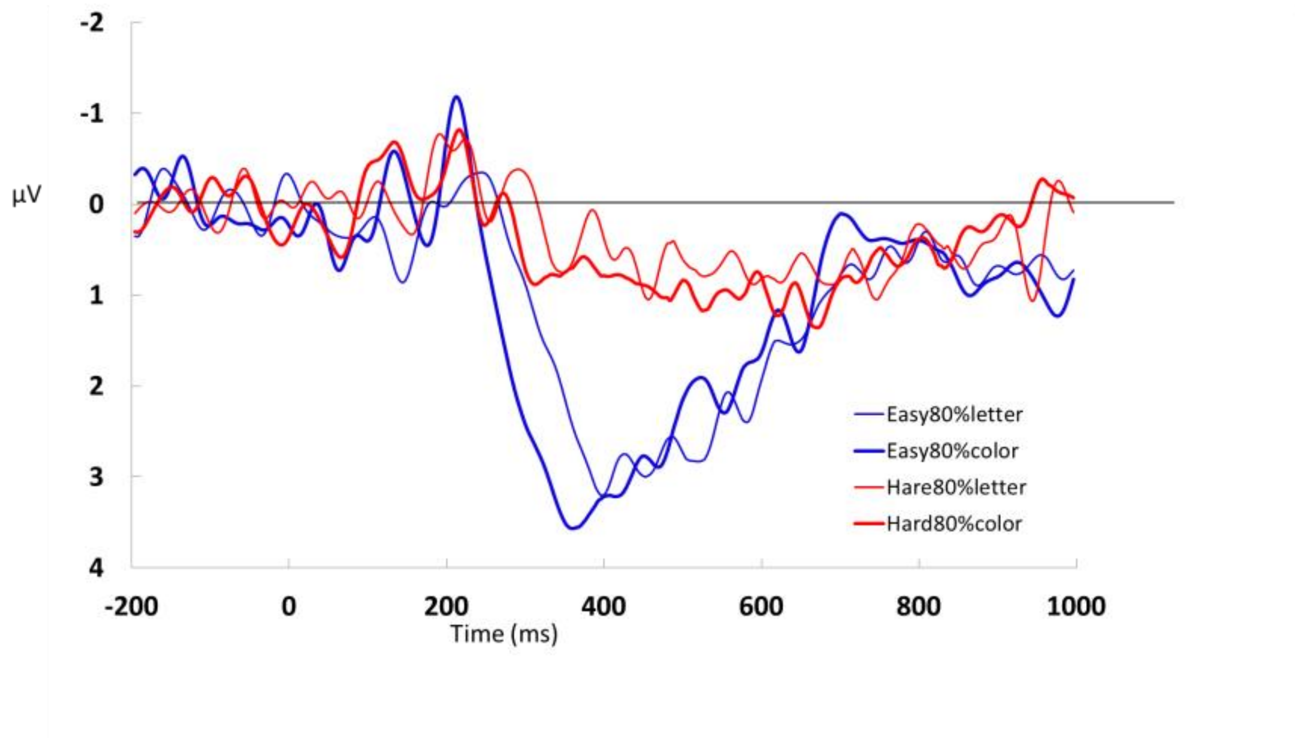
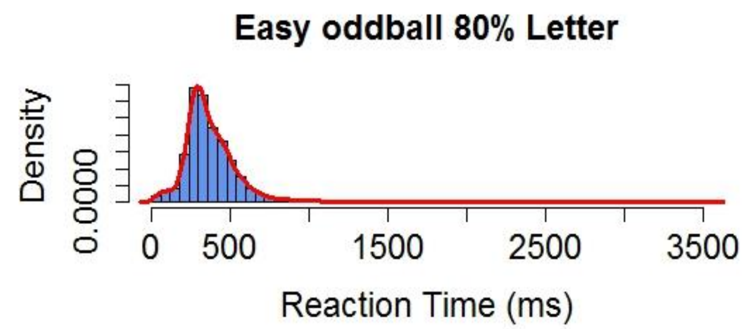
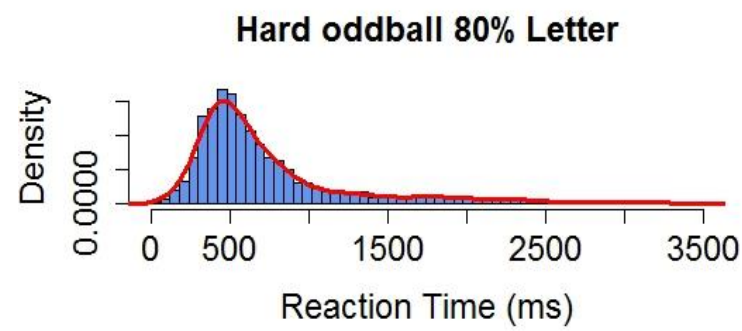
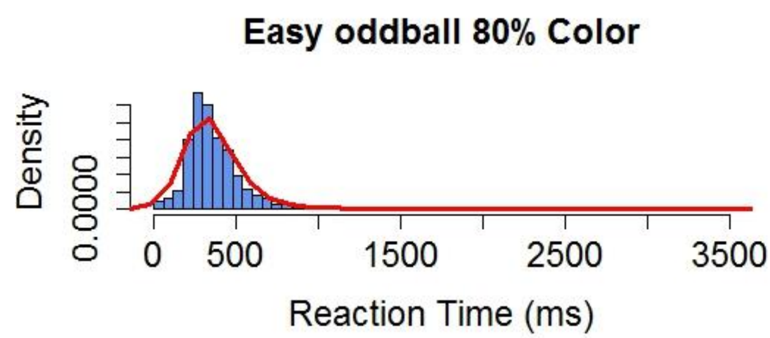
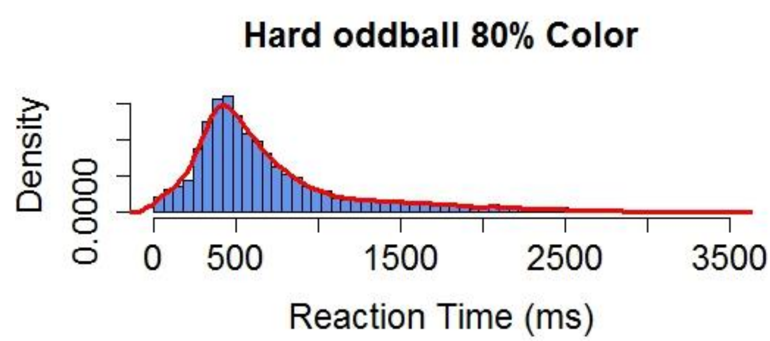


Figure 4. ERP differences: rare minus frequent waveforms


Easy oddball 80% Letter
Density
0.0000
0
500
1500
2500
3500
Reaction Time (ms)


Hard oddball 80% Letter
Density
0.0000
0
500
1500
2500
3500
Reaction Time (ms)


Easy oddball 80% Color
Density
0.0000
0
500
1500
2500
3500
Reaction Time (ms)


Hard oddball 80% Color
Density
0.0000
0
500
1500
2500
3500
Reaction Time (ms)

Tasks	mu	sigma	tau
Easy oddball 80% letter	286.5	110.2	68.4
Hard oddball 80% letter	356	170	262
Easy oddball 80% color	262.8	105.3	80.5
Hard oddball 80% color	328	205	275

Figure 5. The ex-Gaussian distribution of reaction time and its parameters

Table 1. The percentage of variance accounted for by each spatial factor

Spatial Factors	Easy Oddball (80% letter)	Hard Oddball (80% letter)	Easy Oddball (80% color)	Hard Oddball (80% color)	Hard Oddball (80% letter) after LJC	Hard Oddball (80% color) after LJC
SF01	0.2463	0.247	0.2568	0.3823	0.3541	0.4573
SF02	0.116	0.2258	0.171	0.1345	0.1196	0.0904
SF03	0.0839	0.0877	0.1151	0.0721	0.0991	0.0818
SF04	0.0803	0.0516	0.0581	0.0722	0.0688	0.0791
SF05	0.0611	0.0433	0.0549	0.0482	0.0589	0.0466
SF06	0.0442	0.0356	0.0259	0.0317	0.0528	0.0328
SF07	0.0366	0.0333	0.0233	0.0284	0.0458	0.0317
SF08	0.0326	0.0287	0.0212	0.0207	0.0383	0.0291
SF09	0.0295	0.0264	0.0173	0.0207	0.031	0.0132
SF10	0.0217	0.0226	0.0158	0.0124	0.0205	0.0121

Table 2. Variance of the retained spatial factors, spatial factor in parietal area, and spatiotemporal factor for P300. E.g., in the easy oddball (80% letter) task, total (10) spatial factors accounted for 75.22% of the total variance and were retained for further analysis. Among these, SF02 accounted for 11.6% of the total variance, SF02TF2 accounted for 2.51% of the total variance.

	Total Spatial factors (%)	Unique spatial Factor (%)	Unique Spatia-temporal factor (%)
Easy oddball (80% letter)	75.22	SF02-11.6	SF02TF2-2.51
Hard oddball(80% letter)	80.2	SF03-8.77	SF03TF2-3.34
Easy oddball (80% color)	75.94	SF02-17.1	SF02TF2-6.84
Hard oddball (80% color)	82.32	SF04-7.21	SF04TF2-2.15
Hard oddball(80% letter) LJC	88.89	SF02-11.96	SF02TF2-3.82
Hard oddball(80% color) LJC	87.41	SF03-8.18	SF03TF3-1.75

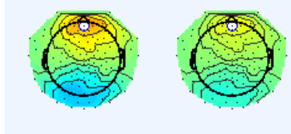
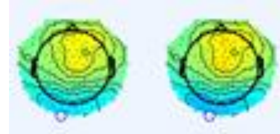
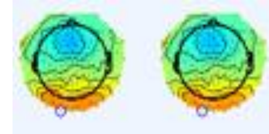
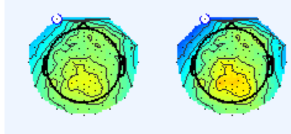
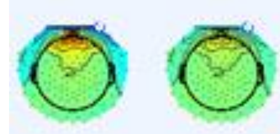
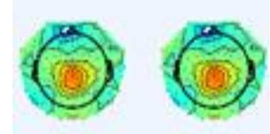
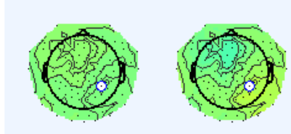
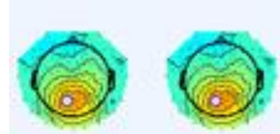
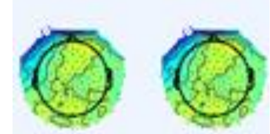
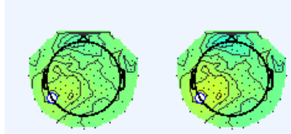
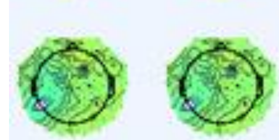
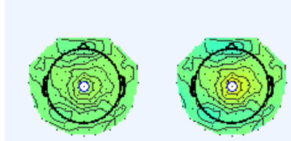
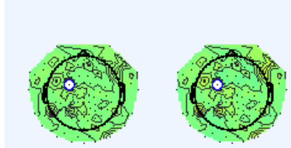
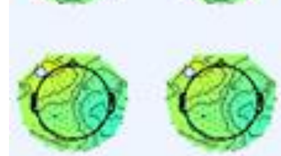
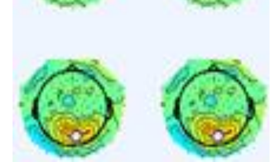
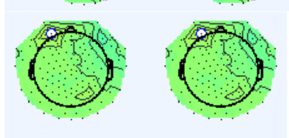
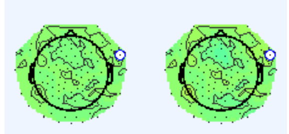
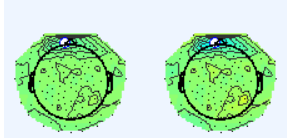
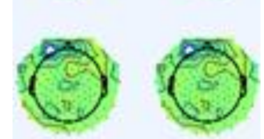
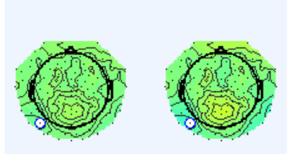
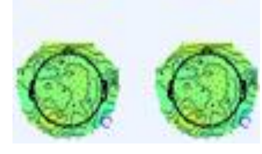
Spatial Factors	Easy Oddball	Hard Oddball	Hard Oddball after LJC
SF01			
SF02			
SF03			
SF04			
SF05			
SF06			
SF07			
SF08			
SF09			
SF10			

Figure 6. Topographic maps of the spatial factor loadings (virtual electrodes), with frequent event on the left, rare on the right. (80% letter above, 80% color below)
(Continued on next page)

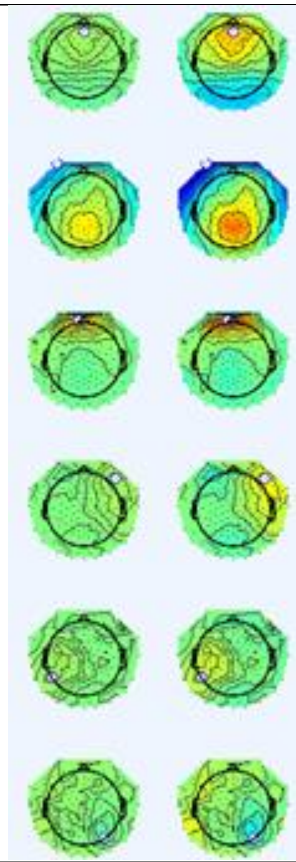
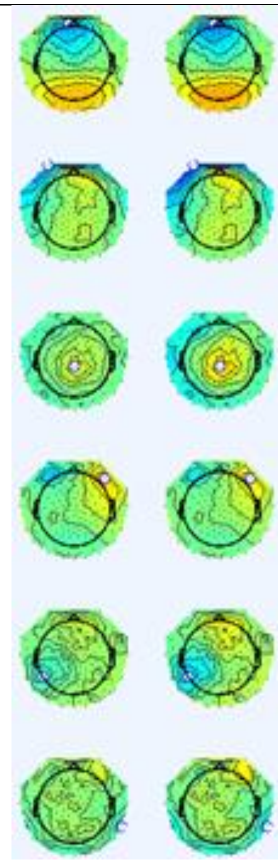
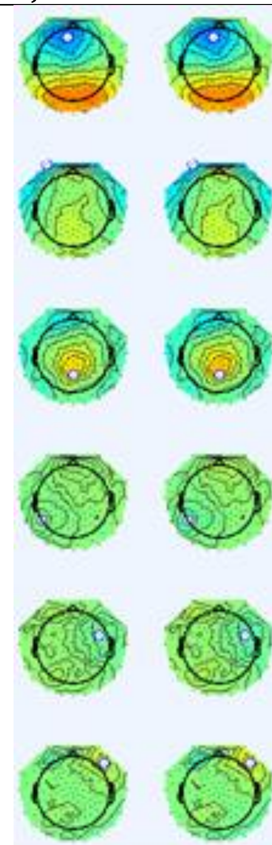
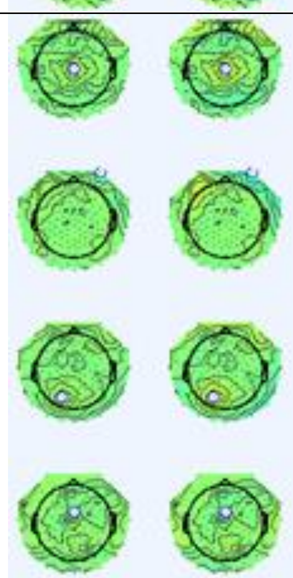
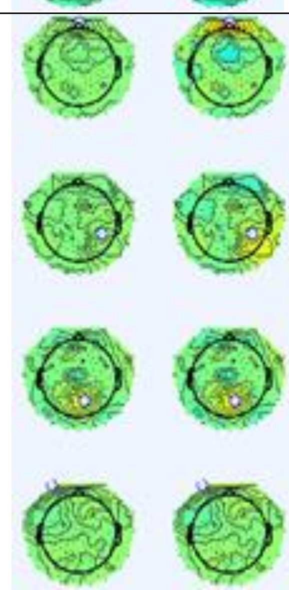
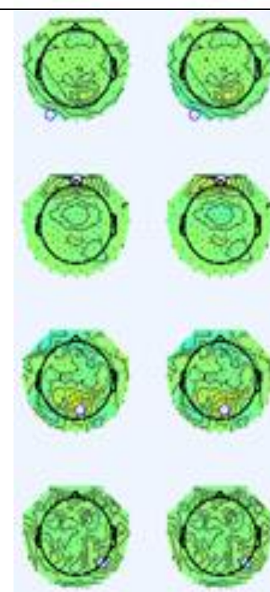
Spatial Factors	Easy Oddball	Hard Oddball	Hard Oddball after LJC
SF01			
SF02			
SF03			
SF04			
SF05			
SF06			
SF07			
SF08			
SF09			
SF10			

Figure 6. Topographic maps of the spatial factor loadings (virtual electrodes), with frequent event on the left, rare on the right. (80% letter above, 80% color below)

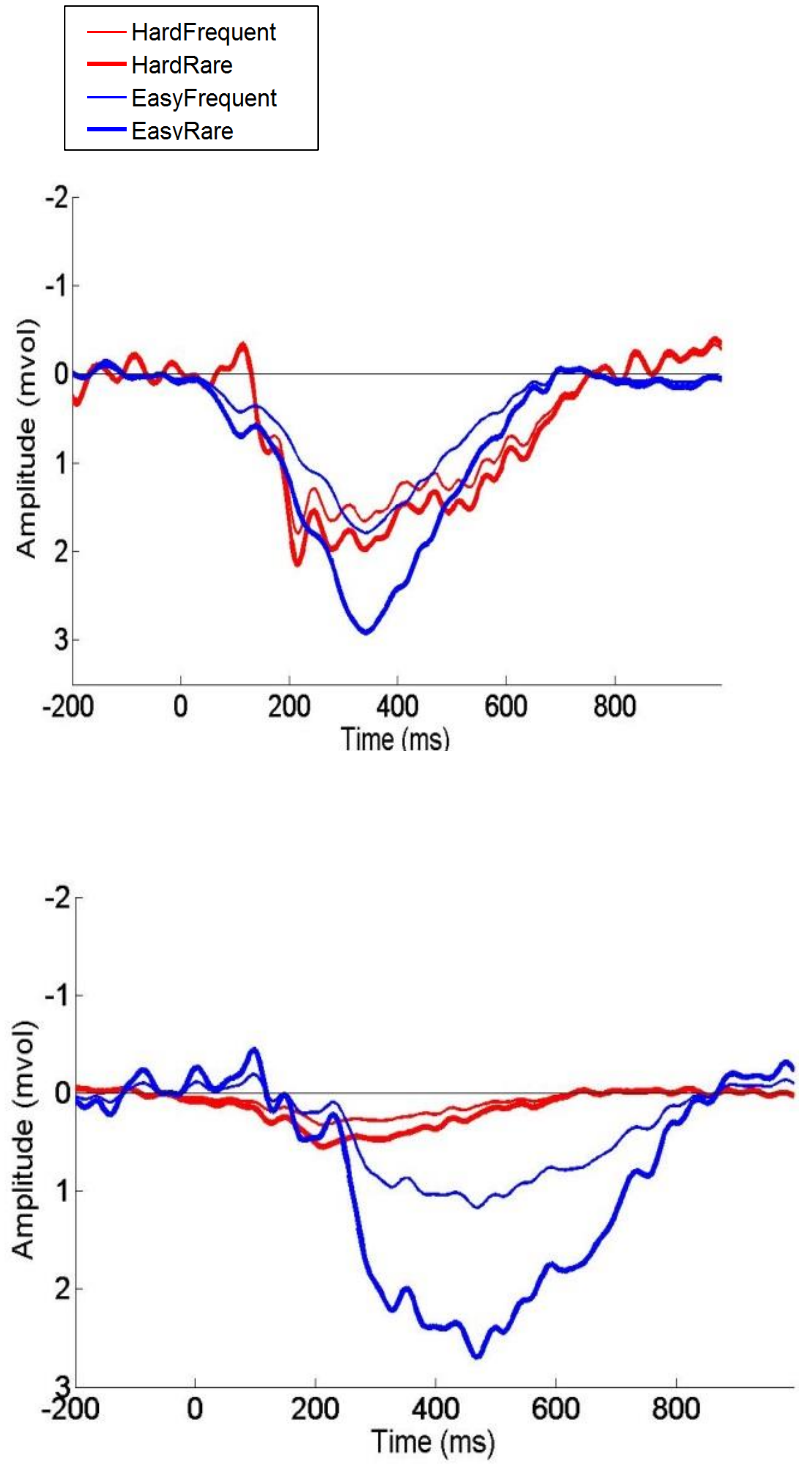


Figure 7. Virtual ERPs for easy and hard oddball tasks (80% letter left, 80% color right)

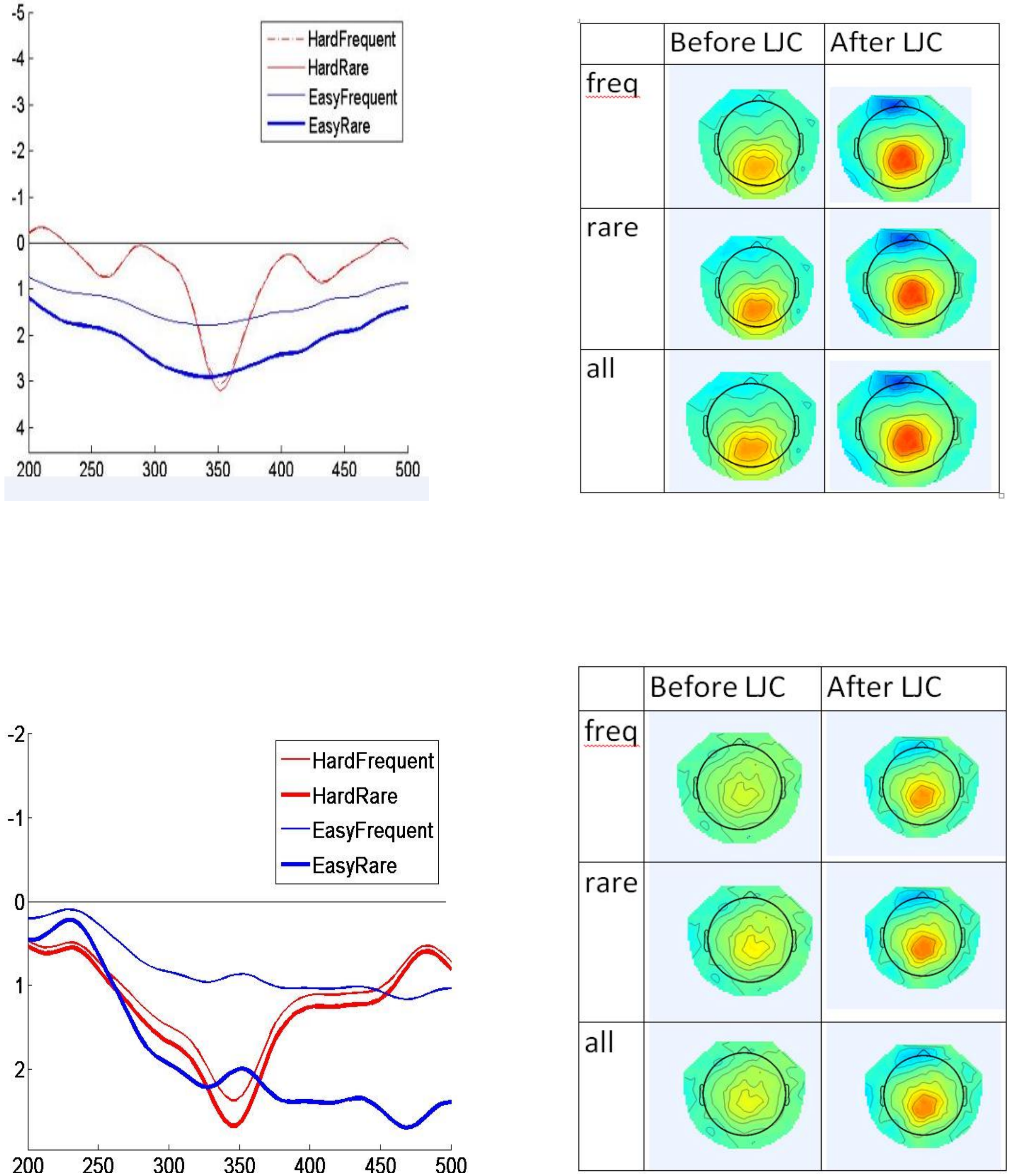


Figure 8. Virtual ERPs and spatiotemporal factors for easy and hard oddball tasks (80% letter left, 80% color right)

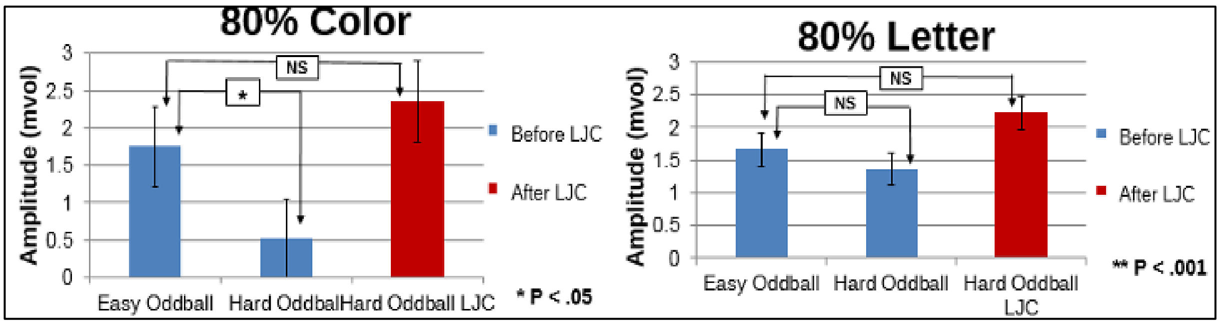


Figure 9. Statistics for Virtual ERPs in the easy and hard oddball tasks

Discussion

Summary of results

16 participants underwent a series of oddball tasks with different decision making requirements and EEG data was concurrently recorded using 128-electrode EGI Geodesic Sensor Net. Unlike a standard oddball task, the current study utilized two stimulus dimensions, letter and frame color. When letter was task relevant, X and U were presented 80% and 20% of the time, respectively. Each letter was presented within either a blue or yellow frame presented with an equiprobable distribution. Similarly, when frame color was the 80/20 feature, letter X and U became equiprobable. The major aim of conducting the above tasks was to investigate the reduction in the P300 amplitudes in the hard oddball tasks, which P300 was considered to be the consequences of latency jitter (i.e. latency variability), and overlapping with other negative ERP components.

Behavioral and ERP data obtained from the current study were similar to that reported in Verleger et al. (2014). In respect to reaction time, participants responded significantly slower in the hard oddball tasks as compared to the easy oddball tasks. This extension in reaction time could be due to the challenging nature of the task, in which both dimensions (letter and frame color) became task relevant, whereas only one dimension was involved in decision making in the easy oddball tasks. As expected, participants also made more incorrect responses during the hard oddball tasks. Again, this could be explained by the increased difficulty in the response selection.

The significant interaction effect of Task × Probability for error rate indicated that subjects were more likely to make mistakes when responding with rare stimuli than frequent stimuli in the hard oddball tasks. Unlike the hard oddball tasks, the amount of errors between rare and frequent stimuli did not significantly differ in the easy oddball tasks. Before any jitter correction was made, the raw ERPs showed a similar pattern of diminished P300 amplitude as in the original study. As predicted, a large P300 was observed in the easy oddball tasks, which is consistent with many other studies which use an oddball task (Donchin, 1981; Houlihan, Pritachard, & Robinson, 1996; Kutas et al., 1977; Polich, 2007). Similarly, a diminished P300 was observed in the hard oddball tasks.

Spatiotemporal PCA was applied to the EEG data to disentangle the overlapping components, the results presented four interpretable spatial factors. The first spatial factor was a positive frontal factor with a peak around 300 ms, its spatial distribution and the temporal characteristics well corresponding to the novelty P3 (P3a) (for a review, see Friedman, Cycowicz and Gaeta, 2001). As found in previous studies, it is common to observe a P3a in an oddball paradigm, since P3a can be elicited by deviant events. As the stimuli occur repeatedly, P3a will reduce because the “novelty” decreases. Because of this characteristic, P3a was reported to habituate quickly (Knight, 1984; Lynn, 1966). In addition, P3a also reflects orienting response (Sokolov, 1990). The second one was a negative deflection with a broad scalp distribution, peaking around 1,000 ms, which is corresponding to the slow wave. An increase in slow wave can be a sign of mental fatigue (Jap et al., 2009), and its amplitude is positively correlate with reaction time (Ruchkin et al., 1980). Noting that slow wave is similar with P300, most robust when elicited by rare stimuli (Duncan-Johnson and Donchin 1977; K. Squires et al. 1977), it is important to examine its overlapping with the P300 (Roth et al., 1978; Ruchkin et al. 1980). The third one was a negative deflection in the centro-frontal area, peaking around 300 ms. ERN peaks within 100 ms after realizing a mistake, considering that the stimuli was presenting for 200 ms, 200 + 100 = 300, this negativity was very likely part of the ERN/FRN. The last interpretable spatial factor was of the interest of this study, it was a positive component with a parietal distribution, well corresponds to the P300. This procedure greatly contribute to the correction of latency jitter as (1) ERP components are disentangled, the P300 component was identified; (2) the spatial factor corresponding to the P300 served as a template in the jitter correction technique, PCA Woody. It will be discussed below.

As indicated in previous studies (Fjell et al., 2008; Karalunas et al., 2014), reaction time was linked to the latency of P300, thus the variation in the reaction time can reflect the amount of variation in the latency jitter. An ex-Gaussian distribution of reaction time data and its parameters (mu, sigma, tau) were created to reflect the amount of jitter in the latency of the P300 (Balota & Yap, 2011; Plourde & Besner, 1997; Spieler, Balota, & Faust, 1996). Consistent with the behavioral data, the mu, which indexes the mean RT of the easy oddball tasks was smaller than in the hard oddball tasks. The larger tau value (the mean and standard deviation of the exponential component) and the larger sigma value (the standard deviation of the Gaussian component) both indicated a larger variation in reaction times during hard oddball tasks than easy oddball tasks. PCA Woody (EP Toolkit; Dien, 2010) was applied to eliminate any latency jitter, and virtual ERPs from the jitter-corrected data showed a significant increase in P300 amplitude, With this correction applied, no significant difference between P300 amplitudes in the easy oddball and hard oddball tasks was observed, suggesting that the P300 amplitude is not related to decision making requirements.

The resulting P300 in the hard oddball tasks did not reflect either the decision making hypothesis of the P300 (Kelly and O'Connell, 2013; O'Connell et al., 2012), or the Stimulus-Response link hypothesis of P300 (Verleger, Schroll, and Hamker, 2013). To reiterate (cf. the hypotheses on P300), the P300 amplitude was expected to increase in the hard oddball task according to the decision making hypothesis, as its difficult requirement needing more effort in decision making process; the P300 amplitude were supposed to be hardly observable based on the Stimulus-Response link hypothesis, because the link of the rare stimuli was too difficult to establish (Verleger et al., 2014). The fact that the P300 amplitude would not change as decision requirements differ can be accounted for by the context-updating theory (Donchin, 1981; McCarthy & Donchin, 1981), that the P300 reflects the process of stimuli evaluation, and is insensitive to the tactical processing of producing a behavioral response (Kamp et al., 2013).

Critique of the rationale and the task design in the original study

The Stimulus-Response link has implied that the elicitation of the P300 needs behavioral response, this can be disproved by many other studies did not use motor response, i.e., silent count, passive viewing (Kayse et al., 2010; Reza et al., 2006). Fjill et al. (2009) has criticized that the relationship between RT and P300 latency would be too simple if based on Verleger's view, P300 represents the process the between stimuli processing and response selection. In addition, Verleger and colleagues (2014) were trying to find a decision making related ERP component in their study, they considered this negative component led to the reduced P300 in the hard oddball tasks. Consider the fact that error trials were not excluded from their analysis, this negative component was likely to be the ERN or FRN.

The reduction in the P300 of a difficult task can be explained by task difficulty. Given the probability of the stimuli remains the same, P300 amplitudes often decrease as task difficulty increased, it could be due to the difficult discrimination of the stimuli, or the increased difficulty in identifying a target because of the consideration of multiple parameters (Magliero et al., 1984; Pfefferbaum et al., 1983; Picton, 1992; Ritter et al., 1983; Verleger et al., 2014), or making the categorization of the stimuli more difficult by requiring simultaneous perceptual processing of several stimulus events (Isreal et al., 1980a; Kramer et al., 1985). Under this circumstance, cognitive capacity is highly consumed by processing multiple stimulus dimensions of a stimulus or several stimulus events (Isreal et al., 1980a; Kok and Looren de Jong, 1980; Wickens et al., 1983; Hoffman et al., 1985). Important to note, P300 latency is often increased when the task becomes more difficult.

A design in the task has been a concern. Although P300 amplitudes were similar in both easy and hard oddball tasks, the oddball seen with rare stimuli was not observed as P300 amplitude were similar in size for both frequent and rare stimuli. This could be due to stimuli categorization in the hard oddball tasks. As categorization of the stimuli is one of the requirements to elicit a P300, Verleger et al.'s (2014) design assumes that participants categorize stimuli the same way that the experimenter intended them to, into the four categories "Blue X", "Yellow X", "Blue Y", "Yellow Y". However, it was possible that participants used a different categorization strategy. For example, stimuli could have been subjectively divided into categories such as "stimuli that require a right hand response" and "stimuli that require a left hand response". As the counterballancing used in the original design places the stimuli into equiprobable categories, the oddball effect of the rare stimuli is not expected to be elicited.

Findings here are consistent with this possibility as no differences in P300 amplitude were detected between rare and frequent stimuli.

Limitations and future application

Several aspects of the study can be improved: The virtual ERPs of the frequent and rare stimuli obtained from the hard oddball tasks were almost overlapped, this was unexpected and the reason for it is not clear. It could be that the EP Toolkit is the most recent version, not being sufficiently tested. It was less likely due to the sample size, although 16 participants were not a big sample, this was sufficient in a study concerning the P300 because the P300can be obtained in single trials. A bigger sample size would be beneficial as more questions can be asked, i.e., learning strategy in the tasks.

Mental fatigue should be taken into consideration in future ERP studies, because its effect on attention is closely related to behavioral performance and neural activities. Researchers have observed a larger negativity in the N1 for irrelevant stimuli, which indicated that subjects were unable to focus on task relevant targets as the increase of fatigue (Boksem, Meijman, & Lorist, 2005), more errors were made and longer reaction time was required. Although the present experiment took less time than the reported 3-hour study conducted by Boksem et al., mental fatigue could still have affected the observed results. To reduce the mental fatigue, a study should give subjects sufficient break during the task. This will also contribute to clean EEG data by reducing the frequency of eye blinks.

It is also important to take overlapping components into account when analyzing ERP data. As we have shown, without running the spatiotemporal PCA analysis, the slow wave component would not have been found to overlap with the P300 (Spencer, Abad, & Donchin, 2000). Thus, assessment of ERPs without addressing overlapping components can result in misleading conclusions.

In conclusion, latency jitter correction is a necessity when analyzing data from a task involving difficult stimuli processing, as it can reduce the mean P300 amplitude when waveforms are averaged across trials. Such variance in latency can be eliminated with latency jitter adjustment techniques, such as Woody filter, as has been shown in previous studies (Kutas et al., 1977; McCarthy & Donchin, 1981; and Spencer, Abad, & Donchin, 2000), or the PCA Woody (EP Toolkit; Dien, 2010) used in the current study. It is also inevitable to have potential overlapping ERP components with target components, PCA has been proven to be an excellent technique to extract target components (Dien, spencer, & Donchin, 2004), which has contributed to a more precise result from the EEG data.

References

Balota, D. A., & Yap, M. J. (2011). Moving beyond the mean in studies of mental chronometry the power of response time distributional analyses.Current Directions in Psychological Science, 20(3), 160-166.

Baur, N., Metzner, M. F., & Śmigasiewicz, K. (2014). The hard oddball: Effects of difficult response selection on stimulus-related P3 and on response-related negative potentials. Psychophysiology, 51(11), 1089-1100.

Cattell, R. B. (1966). The scree test for the number of factors. Multivariate behavioral research, 1(2), 245-27

Coles, M. G., Smid, H. G., Scheffers, M. K., & Otten, L. J. (1996). Mental chronometry and the study of human information processing.Electrophysiology of Mind, 86-131. doi:10.1093/acprof:oso/9780198524168.003.0004

Dawson, M. R., &CONFORTO, D. (1987). The independent processing of features and of locations during visual perception. Manuscript submitted for publication.

Dawson, M. R. (1988). Fitting the ex-Gaussian equation to reaction time distributions. Behavior Research Methods, Instruments, & Computers, 20(1), 54-57. doi:10.3758/bf03202603

Dehaene, Stanislas, Posner, Michael I., & Tucker, Don M. (1994). Localization of a neural system for error detection and compensation. Psychological Science, 5(5), 303-305.

Dien, J., Spencer, K.M., and Donchin, E. (2004). Parsing the "Late Positive Complex": Mental Chronometry and the ERP components that inhabit the neighborhood of the P300, Psychophysiology, 41, 665-678.

Dien, J. (2010). The ERP PCA Toolkit: An open source program for advanced statistical analysis of event-related potential data. Journal of neuroscience methods, 187(1), 138-145.

Donchin E, Ritter W, McCallum C. Cognitive psychophysiology: the endogenous components of the ERP. In: Callaway P, Tueting P, Koslow S, editors. Brain-event related potentials in man. New York: Academic Press; 1978. pp. 349–411.

Donchin, E. (1981). Surprise! . . . Surprise? Psychophysiology, 18, 493–513

Donchin, E., & Coles, M. G. (1988). Is the P300 component a manifestation of context updating. Behavioral and brain sciences, 11(3), 357-427.

Duncan-Johnson, C. C., & Donchin, E. (1977). On quantifying surprise: The variation of event-related

potentials with subjective probability.Psychophysiology, 14(5), 456-46

Duncan-Johnson, C. C., & Donchin, E. (1982). The P300 component of the event-related brain potential as an index of information processing. Biological psychology, 14(1), 1-52.

Falkenstein, M., Hohnsbein, J., & Hoormann, J. (1994). Time pressure effects on late components of the event-related potential. Journal of Psychophysiology, 8, 22–30.

Fjell, A. M., Rosquist, H., & Walhovd, K. B. (2009). Instability in the latency of P3a/P3b brain potentials and cognitive function in aging. Neurobiology of aging, 30(12), 2065-2079.

Friedman, D., Cycowicz, Y. M., & Gaeta, H. (2001). The novelty P3: an event-related brain potential (ERP) sign of the brain's evaluation of novelty.Neuroscience & Biobehavioral Reviews, 25(4), 355-373.

Gehring, W. J. (1992). The error-related negativity: Evidence for a neural mechanism for error-related processing (Doctoral dissertation, University of Illinois at Urbana-Champaign).

Gehring, William J., Goss, Brian, Coles, Michael G., Meyer, David E., & Donchin, E. (1993). A neural system for error detection and compensation. Psychological Science, 4(6), 385-390.

Gehring, W.J., Willoughby, A.R., 2002. The medial frontal cortex and the rapid processing of monetary gains and losses. Science 295, 2279–2282

Gehring, William J., Himle, Joseph, & Nisenson, Laura G. (2000). Action-monitoring dysfunction in obsessive-compulsive disorder. Psychological Science, 11(1), 1-6.

Gonsalvez, C. J., Barry, R. J., Rushby, J. A., & Polich, J. (2007). Targetto-target interval, intensity, and P300 from an auditory single-stimulustask. Psychophysiology, 44, 245–250.

Heathcote, A., Popiel, S. J., & Mewhort, D. J. K. (1991). Analysis of response time distributions: An example using the Stroop task. Psychological Bulletin, 109, 340–347. doi:10.1037/0033-2909.109.2.340

Hillyard, S. A., & Kutas, M. (1983). Electrophysiology of cognitive processing. Annual Review of Psychology, 34, 33–61.

Hockley, W. E. (1982). Retrieval processes in continuous recognition. Journal of Experimental Psychology: Learning, Memory, and Cognition, 8(6), 497-512. doi:10.1037/0278-7393.8.6.497

Hoffman, J.E., Houck, M., MacMillan, F. and Simons, R.F. Event-related potentials elicited by automatic targets: a dual-task analysis. J. exp. Psychol.: Hum. Percept. Perform., 1985, 11: 50-61.

Hohle, R. H. (1965). Inferred components of reactiontimes as functionsof foreperiod duration. Journal of Experimental Psychology, 69, 382-386.

Holroyd, C. B., Nieuwenhuis, S., Mars, R. B., & Coles, M. G. (2004). Anterior cingulate cortex, selection for action, and error processing.Cognitive neuroscience of attention, 219-231.

Houlihan, M. E., Pritchard, W. S., & Robinson, J. H. (1996). Faster P300 latency after smoking in visual but not auditory oddball tasks.Psychopharmacology, 123(3), 231-238.

Isreal, J. B., Chesney, G. L., Wickens, C. D., & Donchin, E. (1980). P300 and tracking difficulty: Evidence for multiple resources in dual-task performance. Psychophysiology, 17(3), 259-273.

Ito, T. A., & Cacioppo, J. T. (2000). Electrophysiological evidence of implicit and explicit categorization processes. Journal of Experimental Social Psychology, 36(6), 660-676.

Jap, B. T., Lal, S., Fischer, P., & Bekiaris, E. (2009). Using EEG spectral components to assess algorithms for detecting fatigue. Expert Systems with Applications, 36(2), 2352-2359.

Jongsma, M. L., Quiroga, R. Q., & Rijn, C. M. (2004). Rhythmic training decreases latency-jitter of omission evoked potentials (OEPs) in humans. Neuroscience Letters, 355(3), 189-192. doi:10.1016/j.neulet.2003.10.070

Kamp, S.-M., Brumback, T., & Donchin, E. (2013). The component structure of ERP subsequent memory effects in the Von Restorff paradigm and the word frequency effect in recall. Psychophysiology, 50, 1079–1093. doi: 10.1111/psyp.12090

Karalunas, S. L., Geurts, H. M., Konrad, K., Bender, S., & Nigg, J. T. (2014). Annual Research review: Reaction time variability in ADHD and autism spectrum disorders: Measurement and mechanisms of a proposed trans-diagnostic phenotype. Journal of Child Psychology and Psychiatry, 55(6), 685-710.

Kelly, S. P., & O’Connell, R. G. (2013). Internal and external influences on the rate of sensory evidence accumulation in the human brain. Journal of Neuroscience, 33, 19434–19441. doi: 10.1523/jneurosci.3355-13.2013

Knight RT. Decreased response to novel stimuli after prefrontal lesions in man. Electroencephalogr Clin Neurophysiol 1984;59:9± 20

Kok, A. and Looren de Jong, H. Components of the event-related potential following degraded and undegraded visual stimuli. Biol. Psychol., 1980, 11: 117-133.

Kramer, A., Wickens, C.D. and Donchin, E. Processing properties: evidence for dual-task integrality. J. exp. Psychol.: Hum. Percept. Perform., 1985, 11: 393-408.

Kutas, M., McCarthy, G., & Donchin, E. (1977). Augmenting mental chronometry: the P300 as a measure of stimulus evaluation time. Science, 197(4305), 792-795.

Magliero, A., Bashore, T. R., Coles, M. G. H., & Donchin, E. (1984). On the dependence of P300 latency on stimulus evaluation processes.Psychophysiology, 21, 171–186. doi: 10.1111/j.1469-8986.1984.tb00201.x

McCarthy, G., & Donchin, E. (1981). A metric for thought: a comparison of P300 latency and reaction time. Science, 211(4477), 77-80.

Luce, R. D. (1986). Response times. New York: Oxford University Press.

Lynn R. Attention, arousal and the orientation reaction, Vol. 3. London: Pergamon, 1966.

M.D. Rugg, M.G.H. Coles (Eds.), Electrophysiology of Mind, Oxford University Press, New York (1995), pp. 1–26

Miltner, W. H., Braun, C. H., & Coles, M. G. (1997). Event-related brain potentials following incorrect feedback in a time-estimation task: evidence for a "generic" neural system for error detection. J Cogn Neurosci, 9(6), 788-798. doi: 10.1162/jocn.1997.9.6.788

Nieuwenhuis, S., Aston-Jones, G., & Cohen, J. D. (2005). Decision making, the P3, and the locus coeruleus norepinephrine system. Psychological Bulletin, 131, 510–532.

Nieuwenhuis, S., Holroyd, C. B., Mol, N., & Coles, M. G. (2004). Reinforcement-related brain potentials from medial frontal cortex: origins and functional significance. Neuroscience & Biobehavioral Reviews, 28(4), 441-448.

O'Connell, R. G., Dockree, P. M., & Kelly, S. P. (2012). A supramodal accumulation-to-bound signal that determines perceptual decisions in humans. Nature Neuroscience, 15, 1729–1735. doi: 10.1038/nn.3248

Pfefferbaum, A., Ford, J., Johnson, R., Wenegrat, B. and Kopell, B.S. Manipulation of P3 latency: speed or accuracy instructions. Electroenceph. clin. Neurophysiol., 1983, 55: 188-197.

Plourde, C. E., & Besner, D. (1997). On the locus of the word frequency effect in visual word recognition. Canadian Journal of Experimental Psychology, 51, 181–194.

Picton, T. W. (1992). The P300 wave of the human event-related potential.Journal of clinical neurophysiology, 9(4), 456-479.

Polich, J. (1987). Task difficulty, probability, and inter-stimulus interval as determinants of P300 from auditory stimuli. Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section, 68(4), 311-320.

Polich, J. (2007). Updating P300: an integrative theory of P3a and P3b.Clinical neurophysiology, 118(10), 2128-2148.

Pritchard WS. Psychophysiology of P300. Psychol Bull. 1981;89:506–540.

Pritchard, W. S. (1981). Psychophysiology of P300. Psychological Bulletin, 89, 506–540. doi: 10.1037//0033-2909.89.3.506

Ratcliff, R. (1978). A theory of memory retrieval. Psychological Review, 85, 59-108.

Ratcliff, R. (1979).Group reactiontimedistributions and an analysis of distribution statistics. Psychological Bulletin, 86, 446-461.

Ritter, W., Simson, R. and Vaughan, H.G. Event-related potential correlates of two stages of information processing in physical and semantic discrimination tasks. Psychophysiology, 1983, 20: 168-179.

Rösler, F., Borgstedt, J., & Sojka, B. (1985). When perceptual or motor sets are changed: Effects of updating demands on structure and energy of P300. Acta Psychologica, 60, 293–321.

Ruchkin, D.S., Sutton, S. and Stega,. M. Emitted P300 and slow wave event-related potentials in guessing and detection tasks. Electroenceph. clin. Neurophysiol., 1980, 49 : 1--14.

Sokolov EN. The orienting response, and future directions of its development. Pavlovian Journal of Biological Science 1990;25:142±50.

Spencer, K. M., Dien, J., & Donchin, E. (1999). A componential analysis of the ERP elicited by novel events using a dense electrode array.Psychophysiology, 36(03), 409-414.

Spencer, K., Abad, E, & Donchin, E. (2000) On the search for the neurophysiological manifestation of recollective experience. Psychophysiology, 37, 494-506

Steiner, G. Z., Brennan, M. L., Gonsalvez, C. J., & Barry, R. J. (2013). Comparing P300 modulations: Target-to-target interval versus infrequent nontarget-to-nontarget interval in a three-stimulus task. Psychophysiology, 50, 187–194.

Spieler, D. H., Balota, D. A., & Faust, M. E. (1996). Stroop performance in healthy younger and older adults and in individuals with dementia of the Alzheimer's type. Journal of Experimental Psychology: Human Perception and Performance, 22, 461–479. doi:10. 1037/0096-1523.22.2.461

Sutton, S., Braren, M., Zubin, J., & John, E. R. (1965). Evoked-potential correlates of stimulus uncertainty. Science, 150(3700), 1187-1188.

Sutton, S. P300 -- thirteen years later. In: H. Begleiter (Ed.), Evoked Brain Potentials and Behavior. Plenum Press, New York, 1979: 107-126.

Van Veen, V., & Carter, C. S. (2002). The anterior cingulate as a conflict monitor: fMRI and ERP studies. Physiology & behavior, 77(4), 477-482.

Van Veen, Vincent, & Carter, Cameron S. (2002). The timing of action-monitoring processes in the anterior cingulate cortex. Journal of Cognitive Neuroscience, 14(4), 593-602.

Verleger, R. (1988). Event-related potentials and cognition: A critique of the context updating hypothesis and an alternative interpretation of P3.Behavioral and brain sciences, 11(03), 343-356.

Verleger, R. (1997). On the utility of P3 latency as an index of mental chronometry. Psychophysiology, 34, 131–156. doi: 10.1111/j.1469-8986.1997.tb02125.x

Verleger, R., Jaśkowski, P., & Wascher, E. (2005). Evidence for an integrative role of P3b in linking reaction to perception. Journal of Psychophysiology, 19, 165–181. doi: 10.1027/0269-8803.19.3.165

Verleger, R., Metzner, M. F., Ouyang, G., Śmigasiewicz, K., & Zhou, C. (2014). Testing the stimulus-to-response bridging function of the oddball-P3 by delayed response signals and residue iteration decomposition (RIDE). NeuroImage, 100, 271-280. doi:10.1016/j.neuroimage.2014.06.036

Verleger, R., Baur, N., Metzner, M. F., & Śmigasiewicz, K. (2014). The hard oddball: Effects of difficult response selection on stimulus-related P3 and on response-related negative potentials. Psychophysiol Psychophysiology, 51(11), 1089-1100. doi:10.1111/psyp.12262

Verleger, R., Schroll, H., & Hamker, F. (2013). The unstable bridge from stimulus processing to correct responding in Parkinson's disease. Neuropsychologia, 51, 2512–2525. doi: 10.1016/j.neuropsychologia.2013.09.017

Wickens, C., Kxamer, A., Vanesse, L. and Donchin, E. The performance of concurrent tasks: a psychophysiological analysis of the reciprocity of information processing resources. Science, 1983, 221: 1080-1082.

Willems, R. M., Van der Haegen, L., Fisher, S. E., & Francks, C. (2014). On the other hand: including left-handers in cognitive neuroscience and neurogenetics. Nat Rev Neurosci, 15(3), 193-201. doi: 10.1038/nrn3679

Woody, C. D. (1967). Characterization of an adaptive filter for the analysis of variable latency neuroelectric signals. Medical and biological engineering,5(6), 539-554

Yeung, N., Botvinick, M. M., & Cohen, J. D. (2004). The neural basis of error detection: conflict monitoring and the error-related negativity. Psychological review, 111(4), 931.