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Processing Load and Biopotentials: An Evaluation of a Consumer Electroencephalogram (EEG)

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Abstract

The general public is extremely interested in mental training and the use of brain imaging to study the mind. One device that combines the two and is currently on the market for consumers is a single channel EEG band produced by NeuroSky which claims to measure concentration. However, the claims that they have developed a single channel measure of concentration and meditation have not been tested. EEG power is related to cognitive memory and performance, which both contribute to concentration. In addition to EEG waves, pupil size is a reliable physiological index of processing load and concentration. The first purpose of this study is to replicate the finding of pupil diameter size and concentration. The second purpose is to see if the results of the replication correlate with the proprietary concentration reading from the NeuroSky single channel EEG as a first step towards understanding what, if anything, consumer EEG equipment measures. In this study we found that found pupil diameter can measure concentration and that a single channel consumer EEG device is also sensitive to concentration.

Processing Load and Biopotentials: An Evaluation of a Consumer EEG

Popular psychology has long fascinated and influenced society at large. In this current age of technology, popular psychology, supposedly based on research, is quickly becoming more available to the layperson. Laypeople want to know more about themselves, and are often willing to pay to find out the secrets of their mind. From devices such as house hold DNA kits to books on dream interpretation, people are interested in knowing about their hidden selves. This is especially true with regard to the use of brain imaging to study the mind (Racine, Bar-Ilan, & Illes, 2005; Racine, Bar-Ilan & Illes 2006). Additionally, with technology rapidly progressing, access to sophisticated devices to measure physiological correlates of mental processes which were traditionally found in a laboratory setting are now becoming available for common and popular use.

The problem with this trend however, is that many of the techniques and devices that are used in the laboratory are being reduced to simplified versions for common use. With this simplification, laypersons are given the impression that interpretation of data from these devices is relatively simple when in reality it is not. Additionally, the data readouts from these simplified devices may not even represent what they are intended to measure.

Research has shown that people are willing to pay a lot of money for things that they think will work, even if in reality they do not (Racine, Bar-Ilan & Illes 2006). Marketers are aware of this fact and consumers are subject to products that claim they are backed by research when in reality they are not.

One device that is currently on the market for consumers is a new dry electrode (EEG) product produced by NeuroSky which claims to measure brain waves or EEG. One of the many brain functions which NeuroSky claims that it measures is concentration or cognitive load. However like many popular psychology device, the claims of this product have not been tested. The purpose of this study is to test the claims of this product using known psychophysiological indices of concentration.

Literature Review

Research has shown that EEG power is related to cognitive memory and performance, all of which contribute to concentration. Specifically, when looking at a traditional EEG readout, alpha bands (a type of brain wave) have been shown to desynchronize with increasing task difficulty and to be positively correlated to cognitive performance (Klimesch, 1999).

In addition to EEG waves, pupil dilation has also been show to measure concentration and task load. Through extensive research, (Kahneman, Tursky, Shapiro, & Crider, 1969; Hoeks, & Levelt, 1993; Bijleveld, Custers, & Aarts, 2009; Granholm & Steinhauer, 2004; Siegle, Steinhauer, Carter, Ramel, & Thase, 2003) pupil size has been shown to be a reliable psychological index of task, processing load, and concentration (e.g. Bijleveld, Custers & Aarts, 2009). Pupil dilation and constriction are controlled by the sympathetic and parasympathetic nervous system (Bear, Connors, & Paradiso, 2007; Bijleveld et al., 2009). In response to any type of stress, the sympathetic nervous system is activated and prepares the body prepares to protect itself. One of the results of the body's response to stress induced situations or challenges is a change in pupil diameter—under stress, the radial dilator muscles of the pupil are stimulated causing the pupil to enlarge in size, when the stress is alleviated the stimulation of these muscles declines and the pupil begin to decrease in size (Siegle, Steinhauer, Carter, Ramel, & Thase, 2003; Granholm & Steinhauer, 2004). Additionally, multiple studies have used pupil diameter as an index of task difficulty. A study by Hooks and colleagues (1993), found that a change in pupil size could be used to measure different levels of attention. A task requiring the most attention to caused individuals' to have the greatest increase in pupil size while a task which required little attentions cased only a slight increase in pupil size. Another study by Kahneman and colleagues (1969), found that when individual engaged in arithmetic tasks of increasing difficulty their pupils also enlarged in size in response to increasing task difficulty, due to the increase in concentration that the task demanded. Thus, by looking at a change in subjects' pupil size relative to experimental events, researchers have demonstrated a reliable index of concentration, attention, and cognitive load.

I therefore propose to use the pupilometric response as a means of verifying claims about the proprietary "concentration" and "meditation" indices computed by the NeuroSky EEG unit. If the NeuroSky product works as it claims it does and measures concentration, when individuals are engaging in a difficult task and wearing the NeuroSky product their EEG readout on concentration should be correlated with a max peak in pupil diameter 2.5 seconds (Kahneman, 1969) after the onset of a difficult or challenging task.

Methods

Experiment 1

Participants: 29 undergraduate students (4 males, 25 females; age: $\bar{X}$ =29.6, SD=1.2) from Andrews University were used in this study. 3 subject were omitted from data analysis due to loss of eye tracking. All participants were recruited for this study were recruited using a participant pool that draws from students in introductory behavioral science classes. All participants received research credit for completing the study.

Materials: Change in pupil dilation was using an Arrington Viewpoint P-60 dark pupil table-mounted infrared eye tracker. The sampling rate was 60 frames per second, and the tracking method was through dark pupil-glint offset. The left eye of each participant was tracked and calibrated using 36 points before the start of the experiment.

Procedure: The procedure for this experiment was taken from a study that examined the effects of an effortful cognitive task on physiological measures, including pupil diameter (Kahneman, et al., 1969). Subjects were tested on three levels of difficulty on a digit transformation task with each level of task difficulty level being blocked into group, with the easiest task requiring participants to add 0, and the most difficult task to add 3. During each task the participants were presented with an audio recording of instructions and a list of 4 randomly selected numbers. The audio recordings for each trial were approximately 25 seconds in length. Participants received audio instructions though a pair of headphones. At the 5 second mark, the audio recording asked participants to add either 0, 1, or 3 to the four serial numbers that would be presented in the future. At 10 seconds the audio recording listed the four random numbers for the respective trial. At 15 seconds the audio recording gave the command "respond" and participants were instructed to respond with their mathematical calculations to the researcher. While the participants were engaging in the mathematical calculation their left eye was being tracked using a 60 Hz dark pupil infra-red eye tracker, with a multicolored computer screen background for the participants to focus on. There were 36 trials in the experiment with 12 trials of each difficulty.

Experiment 2

Participants: 31 undergraduate students (8 males, 24 females; age: $\bar{X}$ = 20.8, SD =2.42), from Andrews University were used in this study. 6 subjects were removed from the data, 2 due to eye tracking loss and 4 due to inadequate EEG recording. All participants for this study were recruited in the same manner as experiment 1. Upon completion of the study participants were rewarded 2 research credits.

Materials: the same methodology and set up from experiment 1 was used with the following modifications: participants had the NeuroSky headband device placed on their head to record EEG wave. The NeuroSky device was connected to the same computer as the eye tracker, used in the previous experiment, via Bluetooth. Both pieces of equipment ran at the same time, on the same computer but on different processors. Additionally a time stamp was placed on both the eye tracking data and the EEG data to match the two data sets.

Procedure: the same procedure as seen in Experiment 1 was used with the addition of the NeuroSky device. During the 36 trials the data from the eye tracker and the NeuroSky device was recorded and time stamped.

Results

Experiment 1

As seen in the 1969 experiment done by Kahneman and colleagues, subjects' pupils dilated in response to increased cognitive load with similar diameter curves (Figure 1 & 2). At the onset of the task, when the individuals were given the instructions to add either 0, 1, or 3, a slight increase in pupil diameter is seen. Following the slight increase, there is a momentary decrease in pupil diameter. Once the cue of numbers are listed to the participants a gradual increase in pupil diameter occurs until its peak in which individuals respond with their answers.

The results of this study are comparable to the 1969 study. One key difference however, was which condition led to the biggest increase in pupil size. The 1969 study found the biggest difference in pupil diameter between the baseline and the add 3. This study found the biggest differences between the baselines and add 1 condition. To test for significance the statistical analysis program, R 3.02, was used to compute, four one-way repeated measures ANOVAs. The four one-way repeated ANOVAS we computed on the following segments: 0-200 frames since list onset, 200-400 frames since list onset, and 400-600 frames since list onset full 600 frame window (10 seconds). Significant values were found for the 400-600 $F(2, 50) = 5.59$, $p = .01$ and the full frame $F(2, 50) = 4.04$, $p = .02$. Non-significant values were found for the 0-200 frame $F(2, 50) = 2.16$, $p = .13$ and the 200-400 frame $F(2, 50) = .06$, $p = .06$.

Experiment 2

Similar eye tracking curves seen in experiment 1 were seen in this study as well, as in study 1 the greatest difference in pupil diameter was found between the add 0 and add 1 condition. Additionally similar curves between the EEG wave and the pupil dilation measurements were seen (figure 3). To test for significance between the two curves the statistical program R, was used to cross correlate the 3 conditions between the eye tracking data and the EEG data. The results show that there are two peaks in the EEG data and only one peak in the eye this pattern is supported by the cross correlational analysis see table 1. For the baseline condition and the add 3 condition we found a positive correlation at the negative lag, and a negative correlation at the positive lag. For both of these conditions the negative correlation at the positive lag was much greater than the positive correlation at the negative lag. For the add 1 condition we also found a positive correlation at the negative lag and a negative correlation at the positive lag; however the positive correlation at the negative lag was much greater than that of the negative correlation at the positive lag. This trend signifies that the EEG data preceded the eye tracking data in the experiment.

Discussion

Experiment 1

As seen in the 1969 study by Kahneman and colleagues the change in pupil dilation curves are almost identical except for the fact that in our study we found the biggest difference between the baseline condition of add 0 and the experimental condition of add 1. This could be due to the fact that as the task difficulty increased individuals began to give up on the add 3 condition. Looking at figure 1, one can see that as the time increased in the experiment pupil diameter increased as well. As the time passed in the experiment individual had to remember the 4 numbers that were presented to them in the cue, and the mathematical instruction and answer to the numbers as well. This taxed working memory and cause increases in concentration as the time of the experiment increase. Right after the subject responded with their mathematical answers a dramatic drop off in pupil diameter was seen. This is most likely due to the fact that the load of the task was then lifted off the subject and they no longer had to engage in extreme concentration. The replication of this study shows that pupil diameter is indeed a reliable index of concentration and task load. It can therefore be used to illuminate the results of the NeuroSky device.

Experiment 2

The same pattern of pupil dilation seen in experiment 1 was seen in this phase of experimentation. In regards to the testing of the NeuroSky device statistical analysis confirms that the device does indeed measure concentration. As would be expected when the participants were engaging in a difficult task the brain would register the task as more difficult and then activate the sympathetic nervous system in response to the stressor. The sympathetic nervous system would then cause a chain reaction in the body to deal with the stress of the experiment and one of those chain reactions would cause an increase in pupil size. The positive correlation at the negative lag that we found in the add 1 condition shows this relationship. The data shows that even though the lines between the EEG waves and the pupil diameter are similar there is a lag between the EEG curve and the pupil diameter curve, with the pupil curve following the EEG curve as expected in the add 1 condition. In the add 0 and 3 conditions some unexpected results were found. A negative correlation at the positive lag for both the baseline and add 3 condition conditions signifies that an increase in pupil size occurred before the brain registered the increased task difficulty and the concentration that it required. This result can be explained by looking at figure 4. In figure 4 one can see that the curves are very similar and can somewhat overlap. However, the EEG, or brain curve has two peaks while the eye curve has only one peak. Due to this difference in curve shape the large dip or lack of peak in the eye curve is driving the data to show a negative correlation at the positive lag. Additionally, the add 3 condition, with a negative correlation at the positive lag is so similar to the baseline condition of add 1 because participants tended to give up on the add 3 condition showing as much effort in that condition as the baseline, add 0 condition.

Furthermore looking at figure 4 one can see that there are two peaks in the EEG curve and only one peak in the eye curve. This phenomenon also seems to suggest that the NeuroSky device is picking up an additional brain processes that eye tracker is not picking up and is more sensitive than was once believed.

The NeuroSky device does work as advertised and may be more sensitive than the producers of the product claim that it is. Laboratory grade EEG devices can cost anywhere from hundreds to thousands of dollars, which limits many small research facilities access to these devices. The single channel EEG from NeuroSky used in this experiment cost less than $100.

One of the limitations of this device however is its sampling rate. Laboratory grade EEG can sample at a rate of 1000 samples/ second while this device can only sample at a rate of 1 sample/ second. Additionally, this device cannot triangulate the source of the EEG components and thus sophisticated ERP studies cannot be done.

With such a low cost and easy accessibility simple EEG studies can be done without the laboratory grade expenses. This device can be used in homes, classrooms, and in simple experiments to teach individuals about their brain and brain imaging. Additionally, the NeuroSky device can be used as another device to measure concentration in eye tracking studies. Thus the NeuroSky device gives researcher another simple tool to use in the lab and consumers the comfort of using a device which they know works. The single channel EEG device is a good first step in converting laboratory grade equipment to a simplified version which is accessible to laypersons, giving individuals access to information which they know is is valid. Hopefully in the future, a more sophisticated device, produced at a lower cost—without all of the limitation of the NeuroSky device, can be developed to be used in a more advanced laboratory setting, and easily accessible to layperson alike.

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Figure 1. The 25 second experiment was split into 4 segments representing different parts of the experiment. Graph 1 (top left corner) shows the change in pupil size since the beginning of the experiment to the directions add (0, 1, or 3). Graph 2 (bottom left) show changes in pupil diameter since the beginning of the direction to the start of when the 4 numbers are listed. Graph 3 (top right) show the change in pupil diameter from the beginning of the 4 number to the start of the participant's response. Graph 4 (bottom right) shows the beginning of individuals' responses to the end of the experiment.

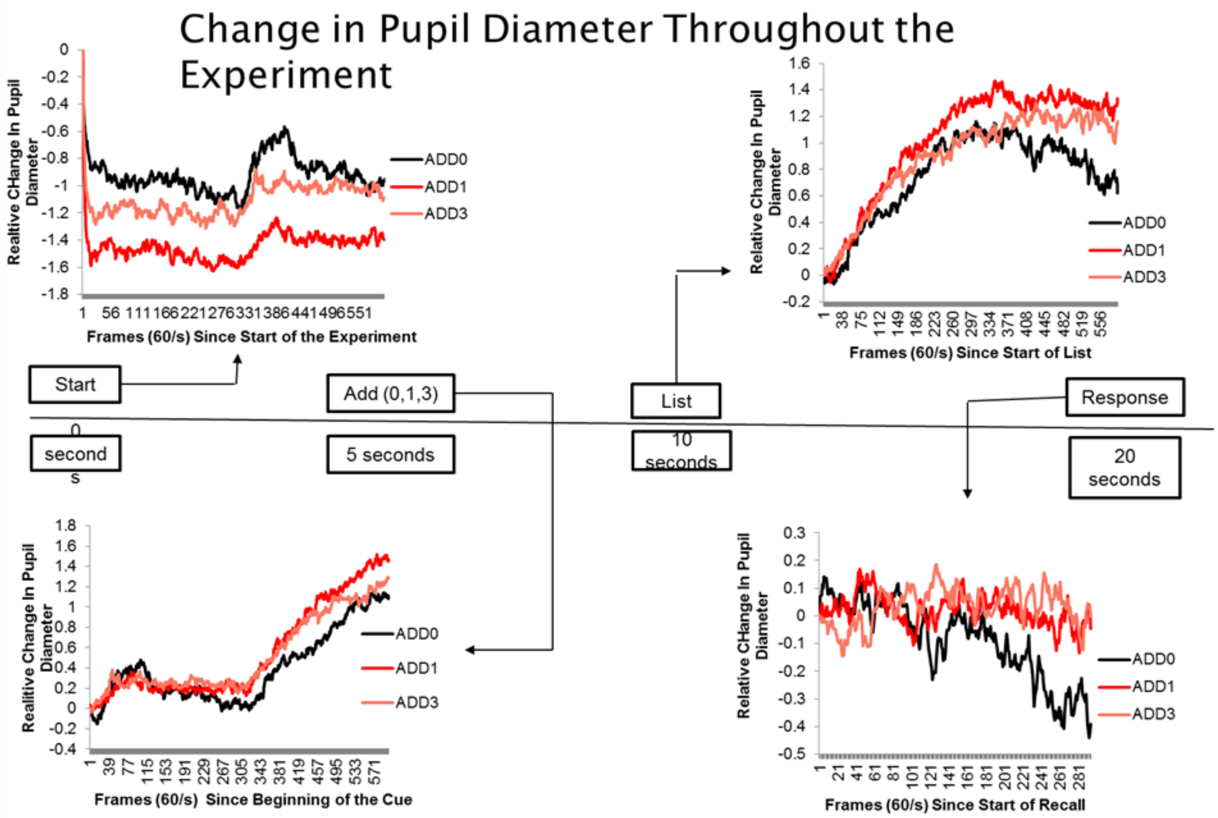

Figure 2. Original graph from Kahneman and colleagues 1969 study. The biggest increase in pupil diameter occurs in the add 3 condition. Additionally in all three conditions at the onset of task an increase in pupil size is seen.

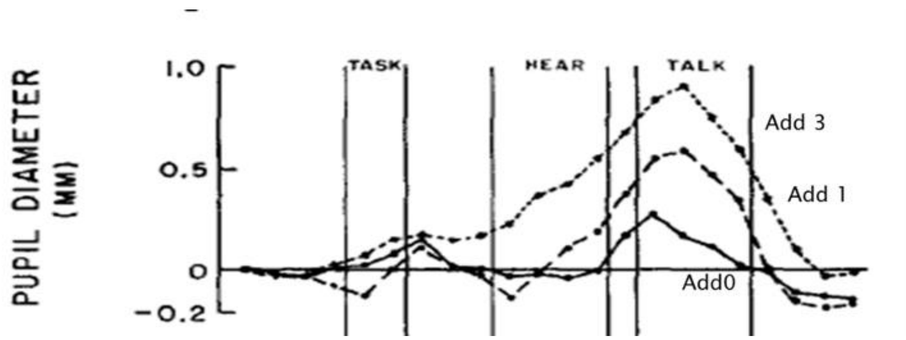

Figure 3. As seen in experiment 1 similar pupil dilation curves are seen in experiment 2. Starting at the beginning of the cue, an increase in pupil dilation is seen until after the recall in which there is a decrease in pupil size.

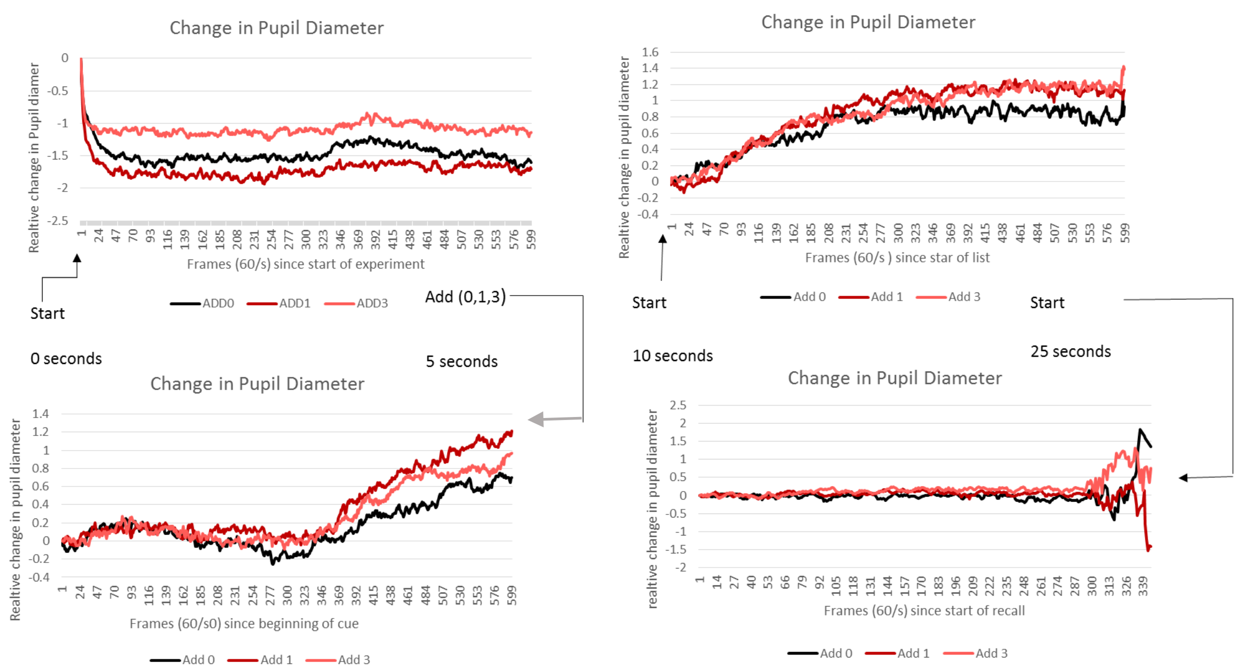

Figure 4. Both curve for the pupil dilation and the EEG concentration data are very similar. One marked difference is that the EEG data shows two peaks while the pupil diameter data only shows one peak. This is due to the fact the NeuroSky single channel electrode is more sensitive than once believed and is picking up brain processes in concentration that the eye tracker is not picking up.

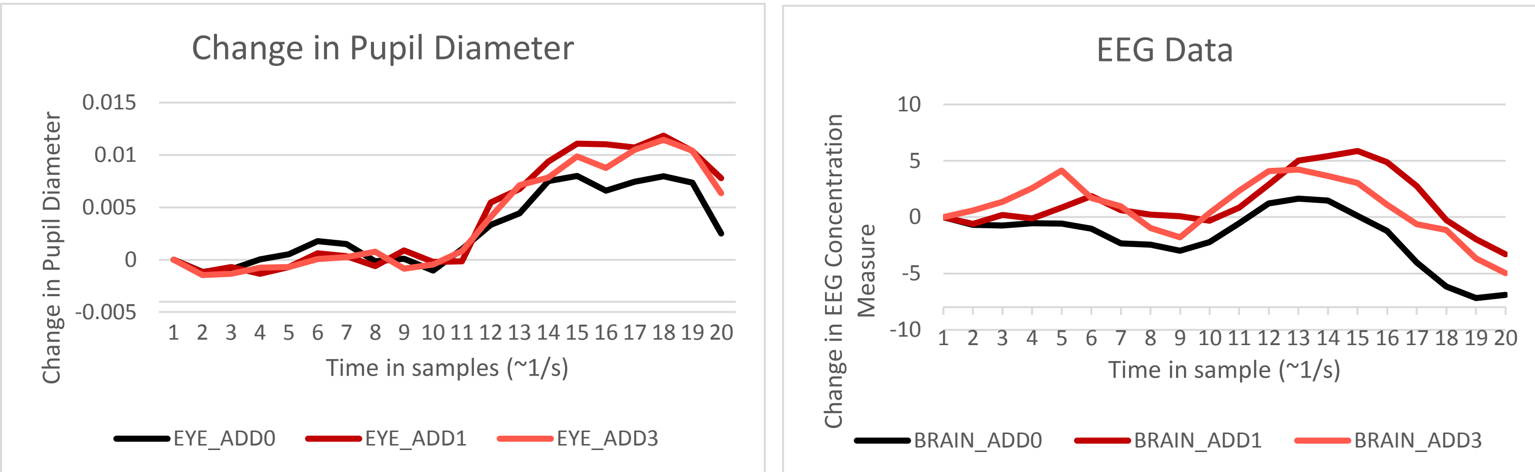

Figure 5. Average Cross-correlation and significance levels of EEG concentration levels and changes in pupil dilation in the study (n=25). Positive lags indicate the pupil dilation data preceded the EEG concentration data, and negative lags indicate that the EEG data precede the pupil dilation data. Positive correlation indicate that the wave between the two lines are moving together and negative correlations that the waves are moving apart.

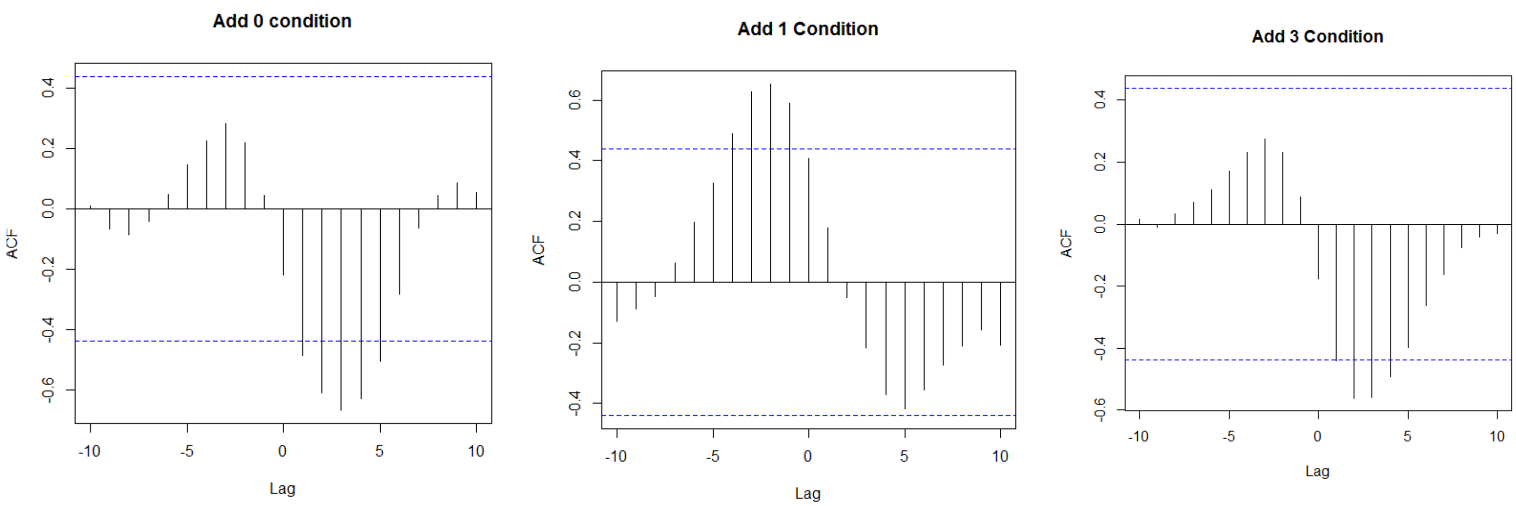

Table 1. Time ranges with cross correlation between pupil dilation and EEG concentration, and the respective pea cross correlation coefficients per time range

			Cross-correlation coefficient	p < 0.05?	Lag (samples; 1 sample/sec)
ADD0	Negative lags	-6 to -1	.284	NO	-3
	Positive lags	0 to 7	-.665	YES	3
ADD1	Negative lags	-7 to -1	.651	YES	-2
	Positive lags	2 to 9	-.417	NO	5
ADD3	Negative lags	-8 to -1	.275	NO	-3
	Positive lags	0 to 8	-.561	YES	2