Brighten up your mind!
Effects of light priming and encouraging feedback on the neural and behavioral responses in a general knowledge task

Master's thesis of Andreea Ioana Sburlea*# (s1107283)

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Abstract

The increase of cognitive demands in society nowadays requires new ways to deal with problems, such as burnout and mental fatigue. Lately, more and more scientifically-based rigorous research in genetic, pharmacological, electrical and optical devices, combined with brain-computer interfaces have been done in the quest for restoring and augmenting cognition. The current research work investigates light, priming and positive reinforcement as possible mediators of cognitive enhancement.

To study the effects of light, priming and positive reinforcement on cognition we set up an experiment where 20 participants are asked to perform a general knowledge task. Different light settings and positive reinforcement are presented in three conditions as a part of the intervention which tries to create a desired state of mind in which the participants perform at their best and link it to a particular light setting. Later, we use this association to test if we can prime cognitive performance. Analysis of behavioral and neural data obtained while performing the task are used as a tool in understanding the underlying cognitive processes.

Our results suggest that the effect of light is not strong enough in the absence of encouraging feedback. It seems that the longer the period with encouraging feedback, the higher the perceived competence of the participants. Perceived competence seems to act as a mediator for good cognitive performance. The analysis of the neural data presents, around 250 - 300 ms, in the frontal cortex, a significant difference in the perception of correct and incorrect feedback. This feature is often attributed to unfavorable outcomes and confirms the importance of the type of feedback.

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Acronyms

BCI	Brain Computer Interfaces
CAR	Common Average Reference
CMS	Common Mode Sense
DC	Direct Current
DRL	Driven Right Leg
EEG	Electroencephalography
EMG	Electromyography
ERP	Event Related Potentials
FIR	Finite Impulse Response
fMRI	functional Magnetic Resonance Imaging
ICA	Independent Component Analysis
ICBE	Internal Committee Biomedical Experiments
IQ	Intelligence quotient
IS	Illumination Setting
PET	Positron Emission Tomography
RGB	Red Green Blue color model
RP	Readiness Potential **(**Bereitschaftspotential)
RT	Reaction Time
SD	Standard Deviation
STM	Short - term memory

1.Introduction

1.1 Your daily burnout

Nowadays, modern society demands start producing increasing psychophysiological stressors that are the precursors to more frequent cases of burnout and mental fatigue. Compared to few decades ago, the average professional spends longer hours in the office with an ever increasing workload, resulting in physical and mental exhaustion.

In general, contexts for cognitive work in complex sociotechnical systems are typified by dynamics, interactions, and context-dependencies – many of which cannot be anticipated as events unfold. In such domains, people do not conduct tasks. They engage in context sensitive, knowledge-driven choice among action sequence alternatives. It only appears as if people conduct tasks when the case at hand is routine, or when a stepwise procedure is mandated. Kludges, work-abounds and local adaptations are an inevitable feature of human interaction with complex information processing systems [1].

At low workloads, subjects tend to lack vigilance and become inattentive, whereas at high workloads their information processing capabilities are exceeded. In today's complex systems, it is primarily at high workloads where human errors due to cognitive failures occur [2].

Humans have begun to race to reverse engineer the brain, understand it and augment it. Towards this end, we are harnessing every trick in the book of mathematics, physics, chemistry, pharmacology, biology, psychology, as well as computer science, information sciences, and engineering – thus giving birth to the AugCog (Augmented Cognition) Era.

Different ways of influencing AugCog, such as light, priming, positive reinforcement or conditioning are presented in the next subsections. A following subsection presents neuroimaging as a measurement of AugCog.

1.2 Augmented Cognition

The area of AugCog research focuses on the development of scientifically-based rigorous genetic, pharmacological, electrical and optical devices, combined with brain-computer interfaces (BCI), for restoring and augmenting cognition (e.g., cochlear implants for restoring hearing or using deep brain stimulations in Parkinson's disease). The effect of various drugs for restoring cognitive functions (e.g., in cases of post-traumatic stress disorders) are also studied and even the possibility of growing living in vitro brain structures and using them as external systems, linked telemetrically and bi-directionally to the patient's brain, is explored. A subfield of AugCog is the study of the relationship between basic operational states of the brain, such as sleep, as well as daily activities such as dance or listening to music and their impact on augmenting cognitive capabilities [3].

The book Foundations of Augmented Cognition explains AugCog in the following way: "The goal of Augmented Cognition research is to create revolutionary human-computer interactions that capitalize on recent advances in the fields of neuroscience, cognitive science, and computer science."

It continues: "Augmented Cognition can be distinguished from its predecessors by the focus on the real-time cognitive [state] of the user, as assessed through modern neuroscientific tools. At its core, Augmented Cognition system is a 'closed-loop' in which the cognitive state of the operator is detected in real-time with resulting compensatory adaptation in the computational system, as appropriate."

1.2.1 Influence of light on cognitive processes

The human eye is sensitive to only a narrow band of electromagnetic radiation, known as the visible spectrum, whose limits depend on the intensity of the radiation involved. These limits define what is meant by the psychophysical term "light" [4].

Light is a pervasive feature of the environment, which exerts broad effects on human behavior. Light already has demonstrated clinical benefits: bright light therapy is an accepted and wide used treatment for seasonal affective disorder [5]. The influence of light has been extensively demonstrated on both animals and humans. Besides the effects of light on physiological functions, light also modulates higher order cognitive processes, like attention or alertness, or emotions like, anxiety or fear [6, 7, 8].

A recent study [16] states that light is not only for vision, but it also represents a powerful modulator of non-visual functions among which, improvement and performance on different cognitive tasks. Light can affect cognitive performance through its synchronizing/ phase-shifting effects on the circadian clock. Thus, prolonged night-time bright light exposure and modifications of sleep–wake schedules can alter the timing of the rhythm in performance on a simple reaction time task. Different studies showed an increase in alertness while being stimulated with blue light. Vandewalle [7, 10] showed that blue light proved superior to other wavelengths in enhancing responses in the left frontal and parietal cortices during a working memory task.

To give more insight on how brain works Horace B. Barlow postulated that "…perceptions are caused by the activity of a rather small number of neurons selected from a very large population of predominantly silent cells. The activity of each single cell is thus an important perceptual event and it is thought to be related quite simply to our subjective experience… A description of that activity of a single nerve cell which is transmitted to and influences other nerve cells, and of a nerve cell's response to such influences from other cells, is a complete enough description for functional understanding of the nervous system"[11].

Brain sites involved in emotional processing participate in the critical function of learning and remembering emotionally arousing effects. This function enables an organism to deal effectively with similar situations when they arise again. In a recent study on mice [9], Warthen et al. hypothesized that light modulates responses to learned fear. They noticed that mice in light freeze more in response to a conditioned tone-cue than mice in darkness. They found that lighting conditions acutely modulate responses when altered between conditioning and testing. This manifestation consists in an increase in freezing when light is added during testing or as a decrease in freezing when light is removed during testing. Their results show that behavioral responses to learned fear, in mice, can be modulated by light. These results contribute to the goal of this research by presenting modifications at the behavioral level due to the intervention of light, as a stimulus.

Colors can relate to our emotions and feelings. For instance, the color blue is associated with comfort and security, orange is perceived as distressing and upsetting, yellow as cheerful, purple as dignifying [8, 12]. The color red has both positive and negative impressions such as active, strong, and passionate, but on the other hand aggressive, bloody, raging and intense. The color green has a retiring and relaxing effect. Green has also both positive and negative connotations such as quietness, naturalness, and conversely tiredness and guilt [13, 14]. According to Birren [15], reactions to color take place independently of thought or deliberation. In his findings on moods, Birren [15] states that warm colors are related to an active behavior, while a cold color resembles a rather passive behavior. Belcher and Kluczny [16], as well as Baron and Rea [17] propose a causal link of affect from luminous environment to cognitive performance via mood. Similar to previous studies, Knez [18] looked into the influence of light on cognitive performance by affecting mood. In his research, he investigated the effect of color of light ("warm", "cold" and artificial "daylight" white lighting) on subjects' self-reported mood and cognitive performance. The "warm" white light (3000K) was more reddish, the "cold" white light (4000K) was more bluish and the artificial "daylight" white lighting (5500K) was even more bluish. The main effects of color of light on short-term memory and problem solving showed that subjects performed better in the "warm" than in the "cold" and artificial "daylight" white lighting. Furthermore, Daggett et al. [19], presented in the context of the effects of colors in the learning environment, an important difference between colors, also described in temperature terms, such as "warm" or "cold" according to the dominant wavelength of the color. The cold colors (e.g., blue, green, purple) are generally considered to be restful and quiet, while the warm colors (e.g., red, yellow, orange) are seen as active and stimulating [12]. We consider that these findings indicate that performing a task under the stimulation of a "warm" color would bring better results in terms of cognitive performance than performing the same task under artificial "daylight" or "cold" colors. These results are enhanced due to the stimulating attributes of the "warm" colors, rather than the more restful ones of the "cold" colors.

1.2.2 Priming and cognition

The relation between priming and memory

Priming refers to an increased sensitivity to certain stimuli due to prior experience. Because priming is believed to occur outside of conscious awareness, it is different from memory that relies on the direct retrieval of information. Direct retrieval utilizes explicit memory, while priming relies on implicit memory. In a study, Schacter [20] discussed about the difference between explicit and implicit forms of memory, by explaining that explicit memory refers to intentional or conscious recollection of prior experiences, as assessed during traditional test of recall or recognition. Implicit memory refers to changes in performance or behavior that are produced by prior experiences on tests that do not require any intentional or conscious recollection of those experiences. Probably the most researched form of implicit memory is known as a repetition or direct priming. Priming can be understood as a form of implicit memory in the sense that it can occur independently of any conscious or explicit recollection of a previous encounter with a stimulus.

The effects of priming with light on cognition and behavior

The effects of light priming have been widely shown in literature mainly in studies done on animals but also on humans [16, 18].

The influence of color on human perception and its effect on cognition and behavior have intrigued many researchers. Some studies present blue and green colors as leading to higher performance than red [21, 22], others record the opposite [23, 24]. Mehta and Zhu [25] report, in their study, findings that demonstrate that red color enhances performance on a detail-oriented task; whereas blue enhances performance on a creative task (see Figure 1.1, Figure 1.2). A set of participants completed a detailed-oriented task (i.e., a memory exercise) presented on computers with red, blue, or neutral background color. They studied a list of 36 words for 2 minutes and were asked to recall as many words as they could after a 20 minutes delay. Three measures confirmed that red indeed enhanced performance on this memory task. Those in the red condition (15.89 ± 5.90) recalled more correct items than those in the blue condition [12.31 ± 5.48; $t(100) = 2.50$, $P < 0.02$; Cohen's $d = 0.64$] (see Figure 1.1).

Furthermore, blue led to more false recalls (0.86 ± 1.29) than red [0.34 ± 0.64; $t(100) = -2.42$, $P < 0.02$; Cohen's $d = 0.52$] or neutral [0.38 ± 0.55; $t(100) = 2.21$, $P < 0.03$; Cohen's $d = 0.48$] condition.

Another set of participants completed a creative task where they were asked to generate as many creative uses for a brick as they could think of within 1 minute. Each participant's responses were coded into three categories: (i) total number of uses generated, (ii) mean creativity score as rated by a panel of judges, and (iii) total number of creative uses. Participants in the three color conditions produced equal number of uses in total ($F < 1$; red, 4.83 ± 2.31; blue, 4.67 ± 2.62; neutral, 4.94 ± 1.68). However, the quality of these uses differed by color conditions. Those in the blue condition (3.97 ± 0.99) demonstrated a higher mean creativity score than those in the red [3.39 ± 0.97; $t(102) = -2.81$, $P < 0.01$; Cohen's $d = 0.6$] or neutral color condition [3.50 ± 0.63; $t(102) = 2.23$, $P < 0.03$; Cohen's $d = 0.57$] (see Figure 1.2) Similarly, those in the blue (1.64 ± 1.46) condition produced more creative uses than those in the red [0.86 ± 0.97; $t(102) = -2.93$, $P < 0.01$; Cohen's $d = 0.64$] or neutral condition [0.91 ± 0.83; $t(102) = 2.70$, $P < 0.01$; Cohen's $d = 0.62$].

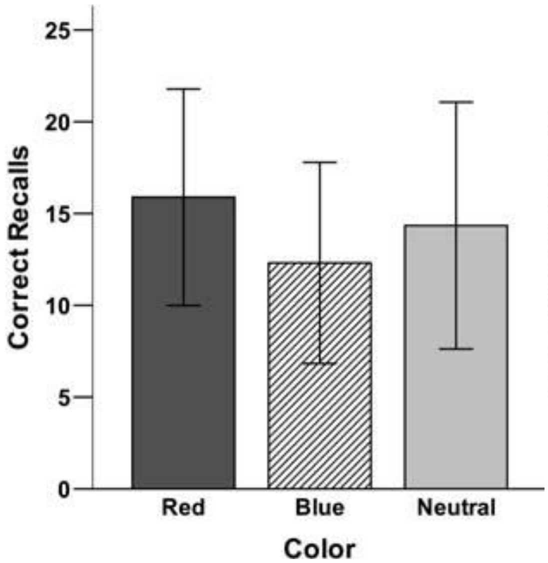


Figure 1.1. Total number of correct recalls for the memory task. $F_{2,100} = 3.15$, $P < 0.05$ Error bars, ±1.00 SD. [25]

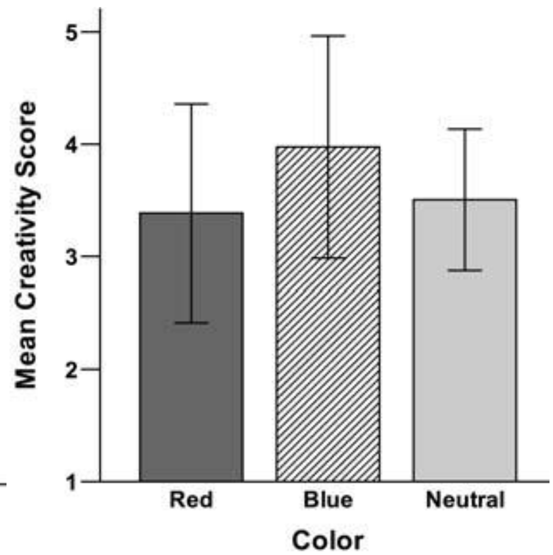


Figure 1.2. Mean creativity scores for the brick task. $F_{2,102} = 4.43$, $P < 0.02$. Error bars, ±1.00 SD. [25]

The obtained results demonstrate that red (versus blue) can enhance performance on detail oriented (versus creative) cognitive tasks. These findings together with the ones from [18] and [19], present warm colors as being more effective modulators of cognitive performance in a memory related task than cold colors.

Effects of priming with fragrance

A related study [26] employing fragrance as a stimulus has achieved an increase in performance of underachieving kids by delivering the same type of stimulation on a consecutive test as in a test where the children performed well.

Stereotype priming

Cognitive performance can also be encouraged through stereotype priming where people are primed to think about a particular person or profession (the stereotype) exhibiting high cognitive ability, prior to engage in a task requiring cognitive ability. In a study reported in [27], it is shown that the performance in a general knowledge task of participants primed with the stereotype of a professor is higher than the performance of participants primed with the stereotype of a hooligan. Similarly, Bargh et al. [28] presented in one of the experiments that participants whose concept of rudeness was primed, interrupted the experimenter more quickly and frequently than did participants primed with polite-related stimuli. In a second experiment, participants for whom an elderly stereotype was primed walked more slowly down the hallway when leaving the experiment than did control participants, consistent with the content of that stereotype. In the third experiment, participants for whom the African American stereotype was primed subliminally reacted with more hostility to a vexatious request of the experimenter.

The influence of priming over insight

A recent study [29] presents the influence of priming over insight and it shows that color not only affects behavior (performance, creativity), but it also suggest that colors exert indirect effects on behavior by modifying the relationship between primed constructs and behavior. Moreover, it demonstrates that stimuli that activate approach (blue) or avoidance (red) are likely to lead to assimilation or contrast, as it is similarly discussed in [30] and [31]. For instance, the perception of red color prior to an important test has been shown to impair performance and this effect appears to take place outside conscious awareness [32].

In a recent study, Spelian et al. [33] present the effect of priming insight. Across four experiments, by exposing participants to an illuminating light bulb, they primed concepts associated with achieving an insight, and enhanced insight problem-solving in three different domains (spatial, verbal and mathematical), but did not enhance general (non-insight) problem solving. Their study explains how visible symbols can influence the generation of insightful solutions to problems; as participants associated an illuminating light bulb with achieving insight, the mere perception of an actual illuminating light bulb brought about mental processes that facilitated the insight process. These results suggest that there is a bond between the illuminating bulb and the mental process.

Effects of priming on decision-making

Research has also shown that the affects of priming can impact the decision-making process [16, 34]. Van Rullen and Thorpe [34] did a study based on visual decision-making process, in which 16 subjects had to press a button if the image on the computer screen that was flashed for only 20 milliseconds contained an animal. In the second task, the same 16 subjects were asked to respond on images belonging to the target category “means of transport”. In each task, half of the non-target images belonged to the other target category. The other half, were distracter scenes that contained no animal or vehicles. The results showed no difference in performance between the animal and vehicle categorization tasks. Percentages correct were around 94% and median reaction times slightly above 350 milliseconds. They also present evidence that categorization could be performed above chance in less than 250 milliseconds, a surprisingly short value which gives an upper limit to the duration of perceptual processes and the beginning of the subject’s decision.

Associative learning and priming

Neutral stimuli can be associated with a certain state of mind or behavior. Generally, the neutral stimulus could be any event that does not result in an overt behavioral response and can be of any modality. For example, humans are not born associating red with stopping. Through the course of life observing and experiencing stop signs, stoplights or brake lights, we begin to consciously or subconsciously associate the red color with stopping.

Solso et al. mentioned associationism in the context of concept formation. They define the principle from the base of this theory as being a bond formed between two events as they are repeatedly presented together [35]. They also mentioned that reinforcement can facilitate formation of the bond. Furthermore, the association principle postulates that the learning of a concept is a result of (1) reinforcing the correct pairing of a stimulus with the response of identifying it as a concept, and (2) nonreinforcing the incorrect pairing of a stimulus with a response of identifying it as a concept. Atkinson et al. [36] described the associative learning process from the perspective of habituation. They outlined the main idea of Wagner [37] who considers that a surprising event is more effectively processed than an expected one. Events are expected or primed if they are already represented in the subject’s short-term memory (STM) at the time they occur. Priming may result from either a recent presentation of the stimulus itself (self-generated) or the presentation of cues that predict the stimulus (retrieval generated or associatively generated). Wagner further explains that within-session decrements in responding, produced by frequent repetitions of the same stimulus, take place mainly because the representation of a recent stimulus is still likely to be active in the STM whenever a new stimulus occurs. The new stimulus is therefore not well processed, and responding is weak. Thus, short-term habituation is basically nonassociative.

1.2.3 Influence of positive reinforcement on cognitive performance

Feedback and reinforcement can be used in a positive way to enhance peoples' feelings of competence, which then increases their intrinsic motivation. This area, called behavior modification, has been developed from animal research in psychology and deals with how the use of reinforcers influences human behavior. The fundamental assumption of behavior modification is that behaviors are strengthened when they are rewarded and weakened when they are punished or unrewarded. The stronger the perceived self-efficacy, the higher the goal challenges people set for themselves and the firmer is their commitment to them [38].

As a support of this theory, Bandura presents a study did by Collins (1982), in which she investigates the way in which perceived-competence contributes to skill utilization. She selected children with three different mathematical abilities: low, medium and high. In each of these categories, she found children who were self-confident with respect to their mathematical abilities and others who had self-doubts. They were presented difficult mathematical problems. The results show that regardless of the category, the children who believed strongly in their capabilities were quicker to discard faulty strategies. They performed more accurately (see Figure 3).

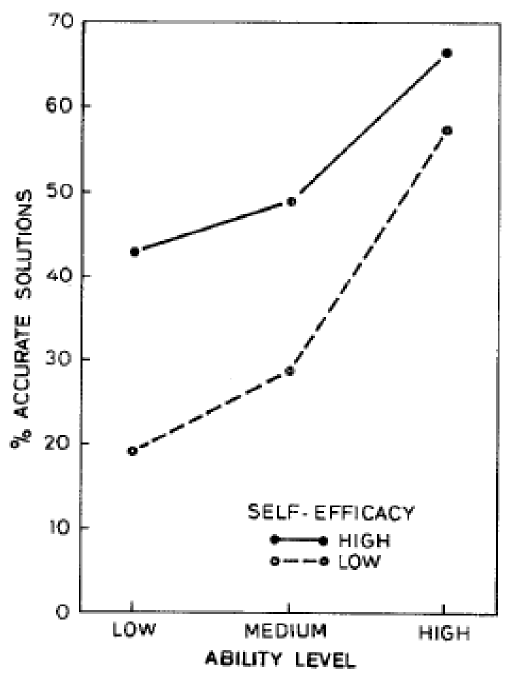


Figure1.5. Mean levels of mathematical solutions as a function of mathematical ability and perceived mathematical self-efficacy [38].

In accordance to the goal of this research, we can conclude from this study that positive reinforcement is an important factor for enhancing both cognitive performance and perceived competence.

In the same study [38], an investigation did by Berry (1987), revealed an interesting connection between memory performance, cognitive effort and self-efficacy (see Figure 1.4). He concluded that the more a participant believes in his memory capabilities, the more time he devotes to cognitive processing of memory tasks. Higher cognitive effort produces better memory performance. Perceived cognitive self-efficacy affects memory performance both directly and indirectly by raising cognitive effort.

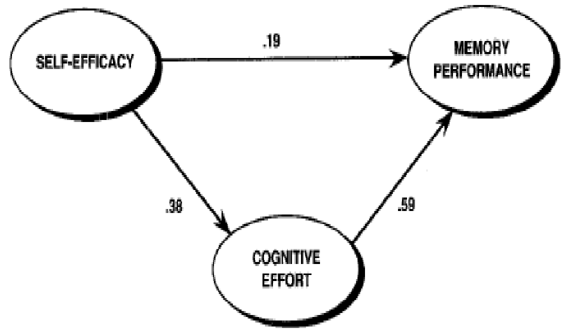


Figure 1.6. Path analysis showing that perceived self-efficacy enhances memory performance directly and by increasing cognitive processing of information [38].

1.2.4 Conditioning

Conditioning occurs through interaction with the environment. There are two major types of conditioning:

Classical conditioning is a technique used in behavioral training in which a naturally occurring stimulus is paired with a response. Next, a previously neutral stimulus is paired with the naturally occurring stimulus. Eventually, the previously neutral stimulus comes to evoke the response without the presence of the naturally occurring stimulus. The two elements are then known as the conditioned stimulus and the conditioned response.

Classical conditioning is the type of learning made famous by Pavlov's experiments with dogs. The gist of the experiment is this: Pavlov presented dogs with food, and measured their salivary response. Then he began ringing a bell just before presenting the food. At first, the dogs did not begin salivating until the food was presented. After a while, however, the dogs began to salivate when the sound of the bell was presented. They learned to associate the sound of the bell with the presentation of the food. As far as their immediate physiological responses were concerned, the sound of the bell became equivalent to the presentation of the food.

Classical conditioning is mainly used for two purposes:

1. to condition (train) autonomic responses without using the stimuli that would naturally create such a response; and
2. to create an association between a stimulus that normally would not have any effect on the participant (a certain light setting) and a stimulus that would (the desire to perform at their best).

Operant conditioning (sometimes referred to as instrumental or Skinnerian conditioning) is a method of learning that occurs through rewards and punishments for behavior. Through operant conditioning, an association is made between a behavior and a consequence for that behavior [45].

We can find examples of operant conditioning all around us. Children completing homework to earn a reward from a parent or teacher, or employees finishing projects to receive praise or promotions, are good examples of operant conditioning.

In these situations, the promise or possibility of rewards causes an increase in behavior, which is also the case of our experiment, but operant conditioning can also be used to inhibit a behavior. The removal of an undesirable outcome or the use of punishment can be used to inhibit or prevent undesirable behaviors. For example, a child may be told they will lose recess privileges if they talk out of turn in class. This potential for punishment may lead to a decrease in disruptive behaviors.

Some key concepts in operant conditioning are:

- Reinforcement is any event that strengthens or increases the behavior that follows them. There are two kinds of reinforcers, positive and negative reinforcers. In our experiment we were using only the positive ones. Positive reinforcers are favorable events or outcomes that are presented after the behavior. In situations that reflect positive reinforcement, a response or behavior is strengthened by the addition of something, such as praise or a direct reward or, in our case, positively biased feedback.
- Sensory stimuli such as olfactory ones can be used to condition cognitive performance. In a recent study [2], fragrance delivery increased the performance of underachieving children at school when the fragrance was previously associated with high performance in a test.

1.3 Related experiment

At the beginning of this journey of exploring the effects of light conditioning and positive reinforcement on cognitive performance, we conducted an experiment searching for the answers to this intriguing research question: Can we enhance cognitive performance with light conditioning?

The essence of this research work [48] can be summarized into three phases: 1) detect (or create) events where a person performs particularly well, 2) apply the targeted light setting with the goal of creating an association between high performance and the light setting, and 3) at a later stage use the light setting to predispose the person for high performance.

We designed the experiment according to these phases and we decided to have three conditions for comparing cognitive performance, a control condition, a congruent condition and an incongruent condition. As cognitive tasks, we chose a Trivia test and an IQ test.

In the control condition, during all three phases the light remained constantly white and no positively biased feedback was delivered. In the congruent condition, during the second phase, also called association and during the test phase, participants were performing the task under the same kind of light, receiving encouraging feedback. In the incongruent condition, light settings changed between the previously mentioned phases, also encouraging feedback was delivered during association and test phases. Participants received feedback about their performance after each trial. The order of the two tests phases was counterbalanced during the experiment.

A questionnaire was introduced after each phase of the task. The purpose of this questionnaire was to register psychological features like, motivation, effort/importance, perceived competence and pressure/tension.

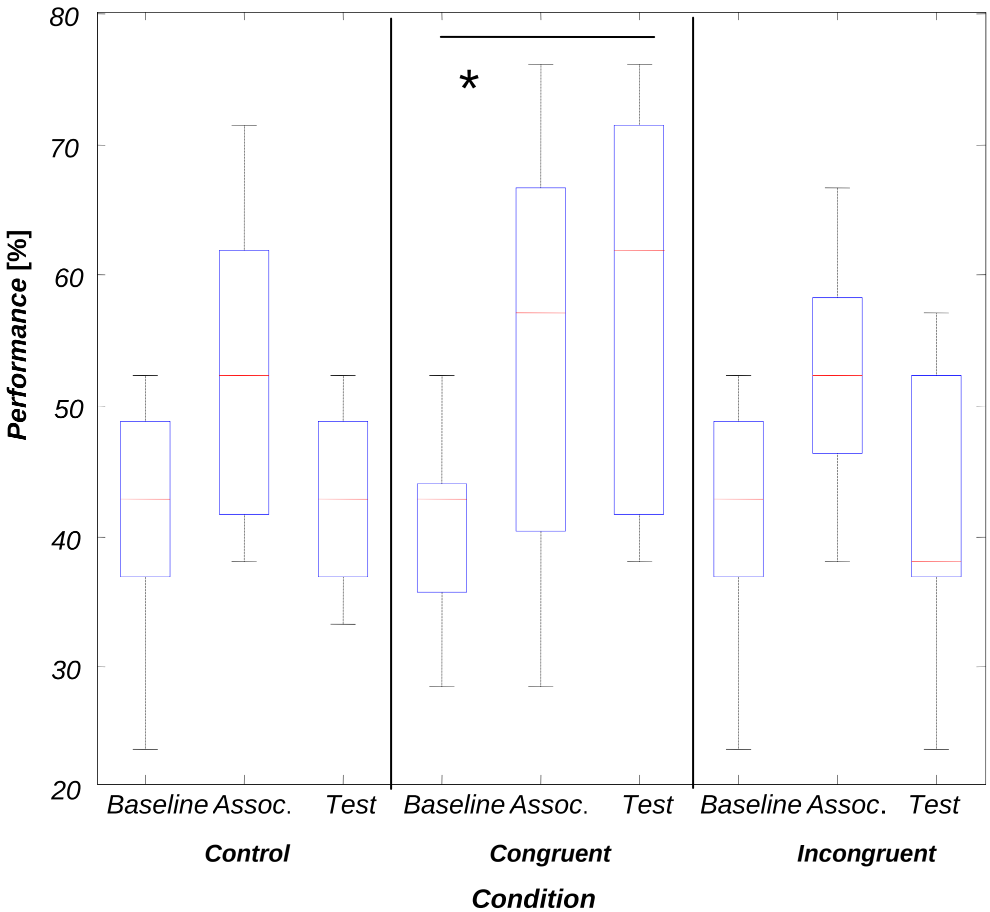


Figure 1.5. Overall performance in each phase of the conditions of the previous experiment [1,2] [50]

Figure 1.5 shows the performance for each condition. It can be seen that the median score of performance in the baseline was similar in all the conditions, having approximately the same variances. The variance performance score was 40% (SD=11.7%). The performance during the association phase of the control condition was very similar to the one of the incongruent condition. The average performance level was 48.7% (SD=11.8). The last phase from the control condition had the same average score as the baseline. In the congruent condition, the performance score during association had larger variance (SD=16.7), average score was 56.3%, higher than the other conditions. In the congruent condition the test phase had large variance, presenting the average score of 56% (SD=12.1). During the last phase of the incongruent condition, the average performance score was 39.8% (SD=11.9). The average level of

[1] The box itself contains the middle 50% of the data. The upper edge (hinge) of the box indicates the 75th percentile of the data set, and the lower hinge indicates the 25th percentile. The range of the middle two quartiles is known as the inter-quartile range.

[2] The star indicates which box-plots are significant after a statistical analysis (ttest).

performance decreased significantly to compared to the same phase during the congruent condition.

The obtained results showed that the participants in the congruent condition, in the Trivia test, had a higher performance than participants in the incongruent condition. This suggests that the increase is affected by the illumination condition under which the task is performed. Furthermore, one of the illumination settings yielded a higher improvement in performance, which suggests that the color of light also plays an important role.

Due do the design choices, we could not discriminate between the effect of light conditioning and the one of encouraging feedback. The analysis of our intervention, consisting of light and positive reinforcement, showed that this enhanced the performance over all conditions. We consider this enhancement to be the effect of an increase in motivation to perform better.

Furthermore, the analysis of the questionnaire yield significant results on the Effort/Importance scale showing that a higher amount of effort was put while performing the last phase of the task in the congruent condition, which also means that performing better during this phase was very important for the participants. The scores of the same scale under control and incongruent conditions had a similar trend, showing that there was no difference in performance in the control and in the incongruent conditions.

Our results revealed that there is no significant influence of the light conditioning and encouraging feedback on the scores of the IQ test, which is not surprising considering the nature of the test. IQ tests are designed to be a stable measure of intelligence.

By comparing the congruent group with the control group in the Trivia test, we could only claim that the improvement is due to both light conditioning and positively biased feedback, because we chose the test phase to have positively biased feedback. We consider that in a follow-up experiment, we can analyze each of the conditions by better dissociating the influence of these two factors.

1.4 Brain activity monitoring

Depending on the research question we are trying to answer, we can use one of three different brain imaging methods: functional magnetic resonance imaging (fMRI), positron emission tomography (PET), or event related potentials (ERP). The main principle behind these methods is the possibility to correlate external events with underlying neuronal activity in a quantitative manner. This is accomplished either indirectly by assessing blood flow (increased neuronal activation means an increase in the need of glucose and oxygen to that area, hence an increase in blood flow needed to transport these nutrients) or directly by recording the small amount of energy emitted from neuronal firing. Each of these techniques provides us with different types of information.

In this paper, we will focus only on EEG – ERP as a method to characterize brain activity.

EEG is a technique which measures electrical potential differences across the scalp, that reflect the underlying neuronal activity of the brain. More specifically, EEG measures particular synaptic activity, excitatory and inhibitory postsynaptic potentials, of cortical pyramidal neurons. It is a non-invasive technique with a high temporal, but limited spatial resolution (when compared to fMRI or PET), and easy to employ in a clinical setting. When the brain processes a stimulus, two types of changes in the EEG may occur: evoked activities, which are exactly time-locked to the stimulus and induced activities, which are changes in the EEG that are not phase-locked to the stimulus.

Event related potentials (ERP) are changes time locked to an event, i.e. the potential occurs either immediately before or after a defined stimulus. This stimulus can originate from either an internal or an external source. ERPs reflect the synchronous and phase locked activities of a large neuronal population engaged in information processing. In other words, the EEG represents spontaneous cortical activity whereas the ERP is generated as a response to specific stimuli and is averaged over a number of samples. However, ERPs can only be generated by neuronal areas that are organized in an open field. If they are organized in a closed field, like the neurons of the cerebellum or the hippocampus, no ERPs will be generated

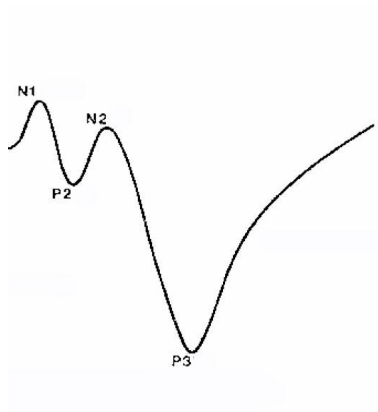


Figure 1.6. ERP curve [49]

When analyzing the averaged, stimulus-locked EEG signal, a number of waveforms ('peaks') can be identified, and characterized by their polarity, order of occurrence, and origin. Components are labeled by their polarity (Positive or Negative) and relative order/time (1 or 100) such that the first positive deflection of an ERP curve is commonly labeled P1, or P100, and they are divided into exogenous or endogenous categories (see Figure 1.6). The exogenous, or early, components of the ERP curve are more a reflection of the initial neural processing of the physical characteristics of a stimulus. These responses are automatic responses to the stimulus and, hence, the magnitudes of these exogenous components are not very dependent on the cognitive processing of the stimulus. The endogenous, or later, components are a more accurate reflection of the neural processing, or cognitive handling of a stimulus. These usually involve "higher" cognitive processes like attention or memory and are sensitive to changes in the meaning of a stimulus or changes in the information processing demand. However, this sensitivity should not be interpreted as a causal link between neurological substrates of cognitive processing and late ERP components, but rather as an indication of correlation between two processes resulting from the same stimulus [49].

In a recent study, Yeung et al. [50] investigated the ERP correlates of positive and negative outcomes. In particular they are presenting the feedback negativity as a large component peaking 250-300 ms after the onset of the feedback, which is maximal over frontal scalp locations.

In one of the experiments, the participants were presented with four colored circles ("balloons") displayed side-by-side, which were containing small monetary wins and losses. The participants were requested to choose one balloon on each trial. There were five blocks of 50 trials each.

After they pressed the button corresponding to their choice, a symbol appeared in the chosen balloon, either "☺" or "☹". The participants were told that the happy face indicates a winning situation (they won 4 cents) and the sad face corresponds to a loosing situation (they lost 2 cents). The difference in the size of wins and losses ensured that participants tended to accumulate winnings steadily throughout the experiment. This manipulation was intended to increase participants' motivation and interest in the task. They were instructed to try to select balloons that contained the good outcomes and they will keep the winnings at the end of the experiment. In the other experiments, there was no choice involved; participants only had to count the number of happy or sad faces, which appeared automatically on the screen.

For the analysis of the ERP data, epochs of 1000 ms were extracted for each feedback stimulus indicating the outcome of the trial. To quantify feedback negativity, they used a window from 248-296 ms.

The feedback negativity was considered to be the difference between loss and gain trials. This difference was significant between 248-296 ms post-stimulus ($F(1,12)=27.0$, $p<0.01$) and it was greater for the choice task than for the no choice task.

One of the appeals of ERP recordings is the ability to relate specific cortical responses to discrete psychological or physiological states and events in a less expensive and less invasive manner than PET or fMRI. Moreover, whereas PET and fMRI techniques generate data that is on a temporal scale of seconds to minutes, ERP recordings are able to provide data on a millisecond scale, thereby allowing a separation, to some degree, of sensory effects from more cognitive effects. In addition to the qualitative characteristics of an ERP curve, information can also be collected from an analysis of its quantitative characteristics, such as peak amplitude, peak latency, peak-to-peak amplitude, and the area under the ERP curve [39].

Unlike, EEG, ERP are broken down into a series of time rather than frequency domain because cells in different locations of the brain become active at different times after a stimulus. The main behavioral impact of cognitive fatigue is a slowing of mental processes, as response times trend to become significantly and progressively higher over time. There appears to be little consensus as to what the different components measure, but it seems that the early components represent the delivery of sensory inputs while the latter correspond to some form of comparison with internal models. Although EEG has less temporal resolution than the ERP, both are susceptible to the same artifacts [40].

However, a concern regarding ERP for AugCog is the increased mental taxation involved in continuous use of the driving stimulus needed to evoke the response. There has been extensive new work on taking ERP measurements from a single event (known as single-trial ERP), a measurement of this kind can be taken very quickly without undue disturbance of the subject [41].

1.5 Objective (Research questions)

Our first aim was to investigate methods to augment cognitive performance. We set out to investigate the effect of light priming and encouraging feedback on cognitive performance. We developed a within-subject experiment in which participants performed a cognitive task (Trivia) under different conditions. Cognitive performance was measured 1) as the number of accurately answered Trivia questions, 2) by the time needed to answer the questions and 3) by the effect of previous feedback on next answer. We expected to observe an increase in performance when delivering the same type of stimulation on a consecutive test as in a test where the participants performed particularly well. This hypothesis is supported by the findings in [26] and [48].

Our second aim was to investigate the effect of light priming and encouraging feedback on motivation of the participants and to address if and how is related to cognitive performance. Thus, we measured not only cognitive performance, but also the motivational factors such as perceived competence and the effort participants put into the task within the different conditions. We expected to observe a correlation between positive reinforcement and perceived competence as is presented in [38].

Our following aim derives from section 1.4 in which we showed that the conventional method to operationalize cognitive performance as a behavioral score may not be sufficiently sensitive to subtle changes. Therefore, our third and final aim was to investigate if ERP analysis can reveal changes in response to positive reinforcement. We expect to see the effect of the unfavorable outcomes as presented in [50].

1.6 Report outline

The thesis is structured into four chapters. In the first chapter we present a summary of previous studies related with this work. Then we present the motivation and the research questions of this study. Chapter 2 presents the experimental design used and the data recording processes. Next we will present the methods used for the data analysis and the materials involved in the data acquisition process. Chapter 3 presents the results of the data analysis and gives answers to our research questions. Chapter 4 presents the interpretation of the results and the conclusions and suggests future options for research.

2. Materials and Methods

2.1 Participants

The participant group consisted of 20 healthy volunteers (10 females and 10 males, Mean age = 27.1 and SD = 5.1). The participants were recruited within Philips Research Campus in Eindhoven. They were highly educated (BSc or MSc degree). They were asked to perform the task either during the morning or the afternoon in both days of the experiment. In the end, they were equally distributed according to the time interval of the day and to their gender. They were randomly assigned to one of three experimental conditions: a control condition, a congruent-first condition or an incongruent-first condition. They were rewarded with a gift certificate of 10 Euro, but they did not know about this reward until the end of the experiment.
All participants read an inform consent letter before coming to the experiment and they were asked to sign it before starting the experiment.

2.2 Task

The task of the experiment was a Trivia test, which consisted of 4 sets of 25 questions in the first day and 3 sets of 25 questions in the second day. The questions were general knowledge questions belonging to seven different knowledge domains and distributed over three levels of difficulty. All the questions were taken from a Trivia quiz [42].

An example of a question and suggested answers is: *"If you suffer from daltonism, you are:"* *a. Color blind, b. Schizophrenic, c. Mute, d. Deaf.*

The level of difficulty of the questions in each session over the two days was similar. In Trivia test, the participants had to select one out of four options. They were told that they have half a minute for each question. The sets were randomized over the task.

EPrime™ software (from Psychology Software Tools Inc) was used for the presentation of the task [44].

2.3 Experimental design

At the beginning of the experiment, the participants were explained the task. Next, they were asked to sign the inform consent letter. Then, the EEG cap was put on. They were looking at a 20 inch LCD screen from a distance of 70 cm. A computer program provided guidance during the test. Initially, the light was turned off. The test started with a short practice session, in which no priming was involved. After the practice, the actual Trivia test started. The light settings were randomly chosen for each participant. After each phase of the experiment the participants were asked to complete a questionnaire on the computer. For further information about the questionnaire see subsection 2.8 and the Appendix A.

This experiment was approved by the Philips internal ethics commission: ICBE (Internal Committee Biomedical Experiments) which is in charge with ethical and methodological situations concerning the experiment. In this investigation, the participants performed the task in two sessions, in two consecutive days. The first session consisted of 4 phases, each of 10 to 15 minutes (see Figure 2.1). The second session, during the second day had 3 phases each of 10 to 15 minutes (see Figure 2.2). The time necessary to complete the task varied across participants. The average time needed to complete the task was 30 minutes in the first day and 20 minutes in the second day. Furthermore, none of the participants used the whole time interval of 45 minutes for the first day and 35 minutes for the second day, to complete the experiment.

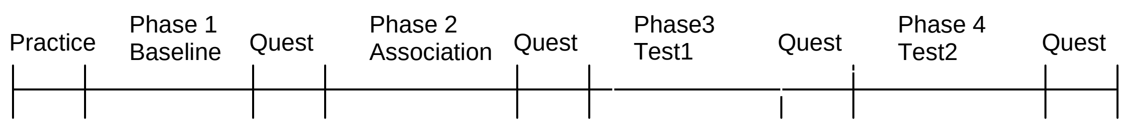


Figure 2.1.Structure of the first day of the experiment

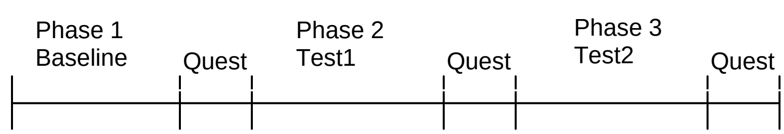


Figure 2.2.Structure of the second day of the experiment. “Quest” refers to the questionnaire introduced after each phase.

The first day of the experiment had four phases, which lead to three different conditions, described in the next subsections and also summarized in Table 2.1 and Table 2.2.

	Conditions (within subjects)		
	Congruent first	Incongruent first	Control
Phases (between subjects)	baseline	baseline	baseline
	association	association	association
	test1 (congruent)	test1 (incongruent)	test1
	test2 (incongruent)	test2 (congruent)	test2

Table 2.1. Design of the first day of the experiment

	Conditions (within subjects)		
Phases (between subjects)	Congruent first	Incongruent first	control
	baseline	baseline	baseline
	test1(congruent)	test1(incongruent)	test1
	test2(incongruent)	test2(congruent)	test2

Table 2.2. Design of the second day of the experiment

2.4 Feedback

Feedback is defined as the knowledge of the results of any behavior, considered as influencing or modifying further performance. In this study we distinguish three types of feedback (see Table 2.3.):

1. True positive feedback – all the questions that were correctly responded received positive feedback
2. True negative feedback – with a probability of 70%, the questions that were incorrectly responded received negative feedback
3. Positively biased feedback – incorrectly answered questions could receive positive feedback with a 30% probability.

Type of feedback	Message displayed on the computer screen
True positive feedback	**Good job!** **Performance x [%]**
True negative feedback	**Incorrect answer** **Performance y [%]**
Positively biased feedback	**Good job!** **Performance x [%]**
In case of not answering in more than 30 sec	No response detected.

Table 2.3. Types of feedback

We use the term "encouraging feedback" to refer to the sum of true positive feedback and positively biased feedback.

The feedback was presented on the screen for 3 seconds, starting immediately after each answer the participant gave (or after 30 seconds), as follows, for both true positive and positively biased feedback the message displayed on the screen was: "Good job!" and the performance in percentage accumulated until that point, for true negative feedback the message was: "Incorrect answer” and the corresponding performance also in percentage. In the case of a not answered question in more than 30 seconds the message displayed automatically after 30 seconds was: “No response detected.” (see Table 2.3).

2.5 Stimuli

The illumination conditions were rendered using 4 Philips LivingColor lamps The light was projected on the walls. The estimated maximum illumination level was below 100 lux.

The colors for this experiment were chosen to be different from each other; complementary colors and not disturbing for the eyes (see Table 2.4). For convenience reasons we will refer to the colors with the terms: green, blue and orange, not because there are pure colors, but according to the most dominant component from the RGB color space, for instance the color Green in our representation has the following RGB value (R=0, G=255, B=80), so it is not a pure green color, but the green component (G) has the highest value. The White color has R=100, because the “pure” white (R=255, G=255, B=255) had some pink shades.

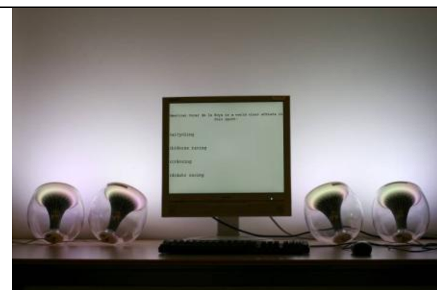
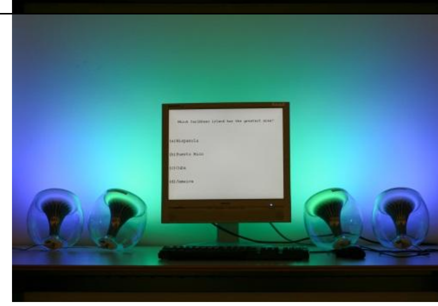
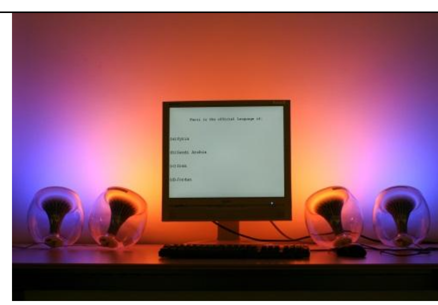
<table>
<tr><th>Color</th><th>R</th><th>G</th><th>B</th><th>illumination setting (IS)</th><th>Picture</th></tr>
<tr><td>White</td><td>100</td><td>255</td><td>255</td><td>IS -0</td><td></td></tr>
<tr><td>Green</td><td>0</td><td>255</td><td>80</td><td rowspan="2">IS - B</td><td rowspan="2"></td></tr>
<tr><td rowspan="2">Blue</td><td rowspan="2">0</td><td rowspan="2">0</td><td rowspan="2">255</td></tr>
<tr><td rowspan="2">IS - A</td><td rowspan="2"></td></tr>
<tr><td>Orange</td><td>255</td><td>165</td><td>0</td></tr>
</table>

Table 2.4. The colors used in this experiment, their RGB code and an illustration of the corresponding set-up

The parameters of the color combinations are presented in the Table2.5.

Color Combination	Horizontal Illumination	Color Temperature	Vertical Illumination	Color Temperature
White	41 lx	4880 K	98 lx	5882 K
Orange-Blue	32 lx	3050 K	75 lx	3516 K
Green-Blue	30 lx	6120 K	69 lx	8717 K

Table2.5. Illumination level and color temperature

According to the presented light settings, the following three different conditions were introduced. In the control condition, during all three sessions the light remained constantly white. In the congruent-first condition, during test1 phase, participants were primed with the same illumination setting as during association. In the incongruent-first condition, the effect of priming with the illumination setting used during association phase was tested in the second test phase. After each trial, participants received feedback about their performance. The order of the two test phases was counterbalanced during the experiment.

2.6 Phases

The task in the first day was structured in four phases: baseline, association, test1 and test2. During **baseline**, the participants performed the task under white constant light. In the **association**, the participants were primed with one of the illumination settings. In the priming phases, participants were performing the task under the same illumination setting as in the association phase during **test1** (congruent-first condition) or during **test2** (incongruent-first condition); and under the other illumination setting, **test2** (congruent-first condition) or **test1** (incongruent-first condition).
The second day is identical from the methodological perspective with the first day, excluding association phase, which was missing.

2.7 Conditions

Control condition. During this condition, the participants performed the task under constant white light and received true positive and true negative feedback in all phases of the experiment.

Congruent-first condition. In this condition, participants that were primed, for example, with IS - A during association, were further stimulated with the same illumination setting during test1 (congruent) and with IS – B during test2 (incongruent). The participants received true positive, true negative feedback and positively biased feedback.

Incongruent-first condition. In this condition, participants that were primed, for example, with IS – A during association, were further stimulated with the other illumination setting during test1 (incongruent) and with IS – A during test2 (congruent). The participants received true positive, true negative feedback and positively biased feedback.

In the first phase, the baseline, the participants performed the task under white light stimulation for all conditions. In the second phase (association), the participants were divided in two groups, one being primed with IS – A and the other with IS - B, while they were performing the same type of task as in the baseline. IS - A and IS - B (see Table 2.6) are two illumination settings with different parameters (hue, saturation, brightness level). In the last two phases (testing), each group was further divided into two groups, in which the participants were stimulated with both illumination settings, depending on the condition. In order to set up the desired mental state, positively biased feedback about the performance was given to the participants only during the association phase.

Phase / **Condition**	**Baseline**	**Association**	**Test1**	**Test2**
Control condition	White light, Trivia test with no positively biased feedback.	White light, Trivia test with no positively biased feedback.	White light, Trivia test with no positively biased feedback.	White light, Trivia test with no positively biased feedback.
Congruent first condition	White light, Trivia test with no positively biased feedback.	**IS – A**, Trivia test with positively biased feedback; true positive and true negative feedback. **IS - B**, Trivia test with positively biased feedback; true positive and true negative feedback.	**IS - A**, Trivia test with true positive and true negative feedback **IS – B**, Trivia test with true positive and true negative feedback.	**IS - B**, Trivia test with true positive and true negative feedback. **IS - A**, Trivia test with true positive and true negative feedback.
Incongruent first condition	White light, Trivia test with no positively biased feedback.	**IS - A**, Trivia test with positively biased feedback; true positive and true negative feedback. **IS - B**, Trivia test with positively biased feedback; true positive and true negative feedback.	**IS - B**, Trivia test with true positive and true negative feedback. **IS - A**, Trivia test with true positive and true negative feedback	**IS - A**, Trivia test with true positive and true negative feedback. **IS - B**, Trivia test with true positive and true negative feedback.

Table 2.6. The design of the experiment

2.8 Psychological features (Questionnaire)

The Intrinsic Motivation Inventory (IMI) is a multidimensional measurement device, which is used to assess participants' motivation on four scales during the experiment (interest/enjoyment, perceived competence, effort/importance and felt pressure and tension scale). During this experiment we used only 2 subscales: Perceived competence and Effort/Importance. The perceived competence concept is theorized to be a positive predictor of both self-report and behavioral measures of intrinsic motivation. Effort is a separate variable that is relevant to some motivation questions, so is used if it is relevant. The questionnaire used in this experiment had a total of 11 questions. Participants gave scores on a 7- point Likert scale (1: not at all and 7: very true). The used IMI questionnaire can be found in Appendix A.

A higher score will indicate more of the concept described in the subscale name. Thus, a higher score on perceived competence means the person felt more competent. Then subscale scores were calculated by averaging the items scores for the items on each subscale.

2.9 Neural data acquisition

EEG signals were recorded with Biosemi™ Active2 signal acquisition system [43]. In Biosemi's equipment the ground electrode is replaced with a common mode sense (CMS) active electrode and a driven right leg (DRL) passive electrode. The location of the electrodes in our experiment was according to the 10-20 system. This 10-20 system is based on the relationship between the location of an electrode and the underlying area of cerebral cortex. The actual distances between adjacent electrodes are 10%, 20% of the total front-back or right-left distance of the skull. This layout ensures that each recording at each scalp site will contain the voltages between each electrode and CMS. We recorded data from 32 channels (Fp1, AF3, F7, F3, FC1, FC5, T7, C3, CP1, CP5, P7, P3, Pz, PO3, O1, Oz, O2, PO4, P4, P8, CP6, CP2, C4, T8, FC6, FC2, F4, F8, AF4, Fp2, Fz, Cz), at a sampling rate of 2048 Hz.

A typical EEG signal measured from an adult human is about 10 μV to 100μV when measured from the scalp. When each waveform represents the difference between two adjacent electrodes, it is referred to as bipolar montage. When each waveform represents the difference between an electrode and a reference electrode, we are talking about referential montage. Usually, the reference position is the mastoid. We used referential montage.

2.10 Signal processing methods

Raw data is digitized with power line noise and blinks and motion artifacts, so it is difficult to separate the signal of interest from the background EEG signal. Therefore, it needs a preprocessing step in this algorithm; which is described in Figure 2.3. We sampled our data at a higher resolution (2048 Hz) in order to capture all the components of interest. At the first step of the preprocessing, we used 50 Hz notch filter with the following specifications for the power line noise removal: FIR band-stop filter (stop band: 49.9-50.1 Hz). During the second step, the samples (each measurement point) were reduced by resampling the data from 2048 Hz to 256

Hz, in order to diminish the time costs of the processing itself.
The third step involved in the preprocessing algorithm is the artifact correction. ICA-based artifact correction can separate and remove a wide variety of artifacts from EEG data by linear decomposition. The ICA method is based on the assumptions that the time series recorded on the scalp:

- are spatially stable mixtures of the activities of temporally independent cerebral and artifactual sources,
- that the summation of potentials arising from different parts of the brain, scalp, and body is linear at the electrodes, and
- that propagation delays from the sources to the electrodes are negligible.

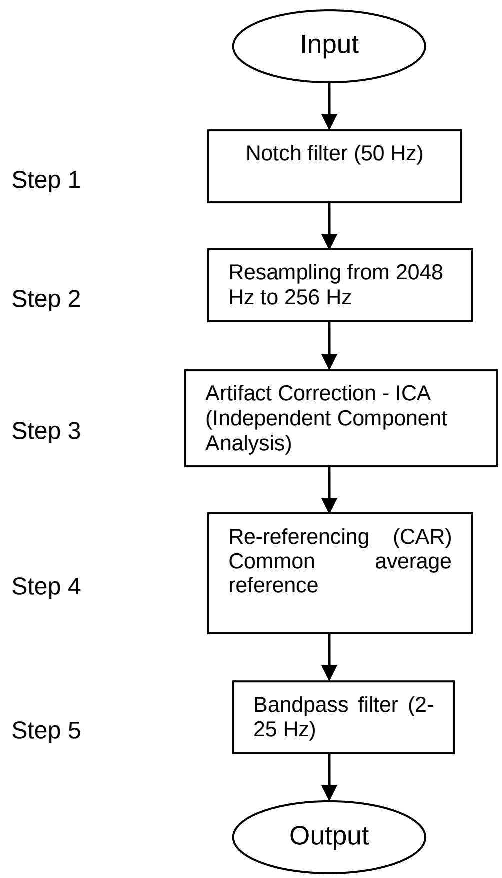
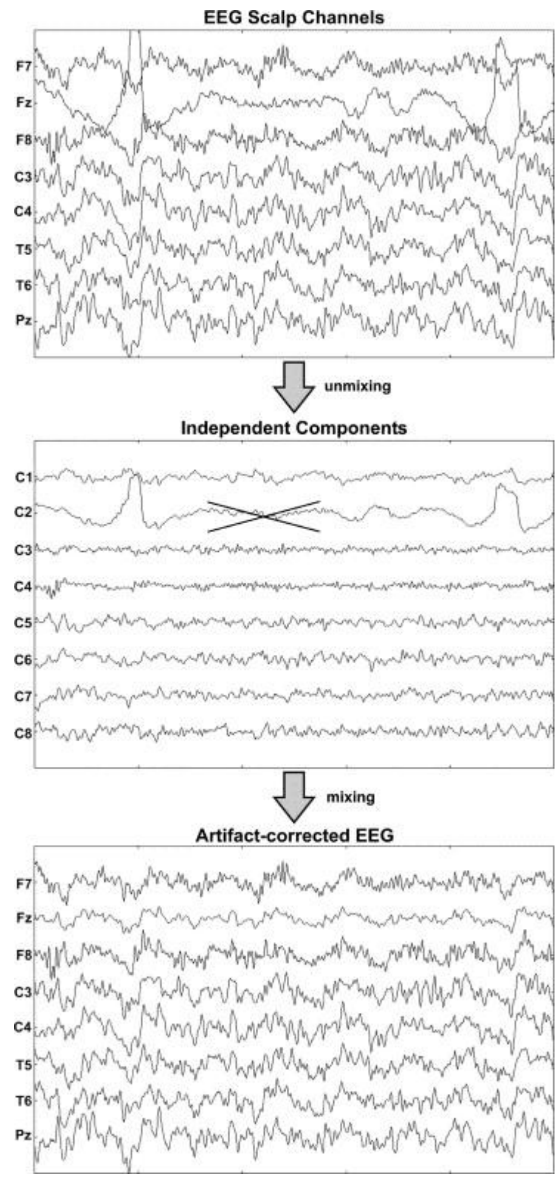


Figure 2.3. Preprocessing steps of the EEG data

Assumptions two and three above are quite reasonable for EEG data. Given enough input data, the first assumption is reasonable as well. The method uses spatial filters derived by the ICA algorithm, and does not require a reference channel for each artifact source. Once the independent time courses of different brain and artifact sources are extracted from the data, artifact-corrected EEG signals can be derived by eliminating the contributions of the artifactual sources (see Figure 2.4).

The fourth step was re-establishing the references. Re-referencing the signal to common average reference consists in subtracting to each sample the average value of the samples of all electrodes at this time.
Fifth, the data was filtered between 2 and 25Hz, because in this frequency range is our signal of interest and to eliminate both low frequency and high frequency components. The usage of this bandpass filter is to eliminate both DC shifts (low frequencies) and to attenuate EMG artefacts (high frequencies), because we are interested in investigating ERPs.



$X = M*S$ (1)

S: independent sources
X: recorded signals
M: mixing matrix

$S = W*X$ (2)
$W=M^{-1}$ (3)

W: un-mixing matrix

Removal of the corresponding column

Figure 2.4. Artifact-corrected EEG [46]

Artifact rejection

We are rejecting the trials in which there are peaks of the signal higher than the sum of the mean of signal and two times the standard deviation of the signal. See the formula below. We consider those peaks as not being part of the signal of interest, but most probably motor artifacts.

$$x_i < mean(\max_j(Xij)) + 2 * std(\max_j(Xij)), \quad (4)$$

where X is the matrix of trials for one channel,

i is the number of samples

j is the number of epochs and

xi is the current epoch.

Segmentation and averaging

The EEG data is recorded continuously, if the activity generated in response to the presented stimulus is the 'expected signal', then the EEG activity not related to presentation of these stimuli can be characterized as 'noise'.

If we assume that this noise is randomly occurring, then by epoching our data, i.e. by splitting it up into trials referenced to the stimulus presentation, and then averaging these epochs together, point-by-point, the noise should cancel out and the activity related to the stimulus should become visible (see Figure 2.5). Signal averaging can improve the SNR by a factor of sqrt(n) where n is the number of terms in the average. A large artifact is hard to attenuate which is why artifact correction is introduced.

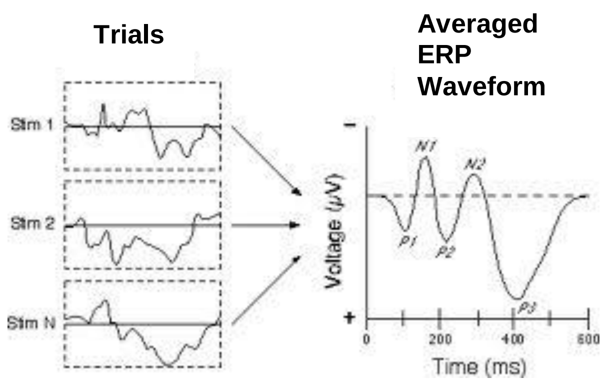


Figure 2.5. Averaging ERP waveforms [47]

The segments are 3000 ms long, from -1000 ms before the stimulus onset to 2000 ms.after the onset of the stimulus. For grand averages, the epochs are considered from -500 ms before the onset of the stimulus to 1000 ms after the onset of the stimulus. In total, before artifact rejection, there are 100 trials for each participant.

2.11 Statistical test

To test if the observed differences are statistically significant, the ttest was applied. The test returns a p-value that takes into account the mean difference and the variance and also the sample size. The p-value is a measure of how likely it is to get this spot data if no real difference existed. Therefore, a small p-value indicates that there is a small chance of getting this data if no real difference existed and therefore decide that the difference in group expression data is significant. A typical significance upper threshold for p is 0.05.

3. Results

This chapter presents the results of our study aiming at answering the following research questions, (1) how cognitive performance is influenced by light priming, (2) what is the effect of light priming and encouraging feedback on participants' motivation and to how is related to cognitive performance and (3) what are the patterns in neural response that correlate with encouraging feedback. First behavior results are discussed, then the intrinsic motivation questionnaire results and finally the analysis of EEG data.

3.1 Effects of augmentation methods on cognitive performance

3.1.1 Effect of light priming and encouraging feedback on accuracy

Overall performance was measured as a percentage of correct answers given by each participant. Failing to provide an answer, which happened in 0.2% of the cases, was considered as a wrong answer. Figure 3.1 shows the performance during all the phases, baseline, association, test1 and test2 of the first day of the experiment. When analyzing this figure, it should be taken into account that test1 and test2 are half shared by congruent-first and incongruent-first conditions. Generally, participants answered 47.3% (SD=11.6) of the questions correct, averaged over all conditions. In the baseline condition participants answered 48.2% (SD=13.8) accurate, during the association condition they answered correctly to 48.3% (SD=10.8), versus 43.7% (SD=7.9) in the test1 condition and 48.8% (SD=13.1) in the test2 condition (see Figure 3.1). A t-test revealed no significant difference of the effect of our intervention.

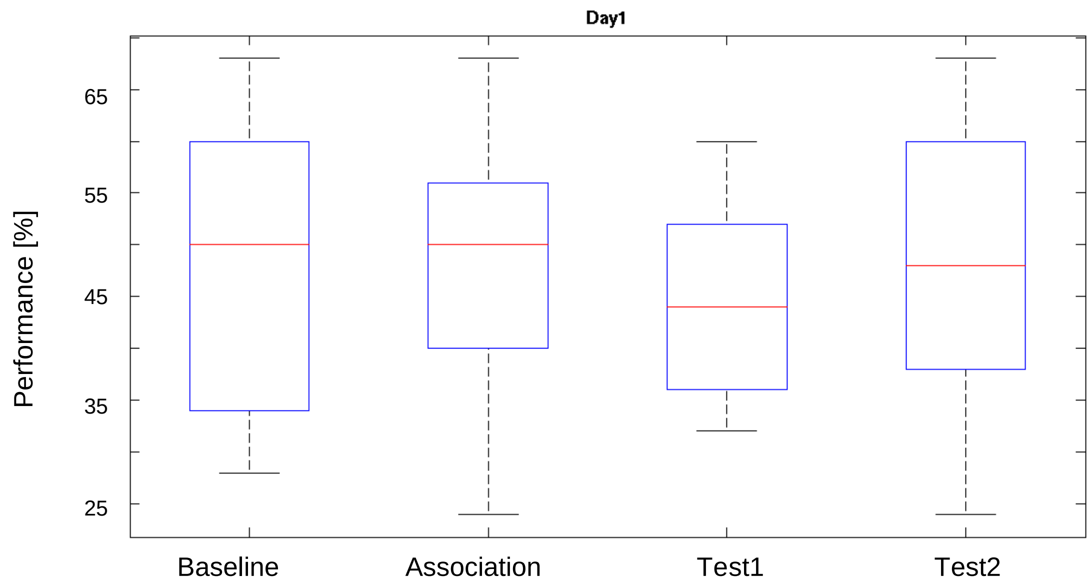


Figure 3.1. Overall performance during the first day of the experiment

While investigating the reason for the smaller variance and reduced score during the third phase (test1), we decided to compare the actual performance and the displayed positively biased performance during association (see Figure 3.2). In average participants' performance, during association, was around 50%, (SD=9.1), while the positively biased performance displayed on the screen indicates in average a level of 70% (SD=7.2).

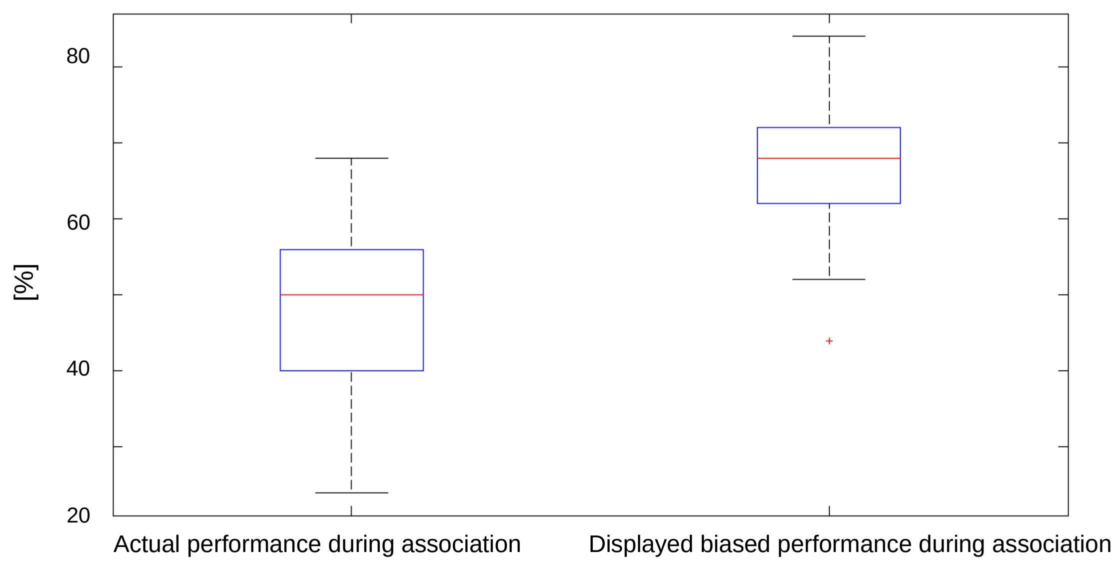


Figure 3.2. Difference between the actual performance and the result of the encouraging feedback during association

The difference between them is not only significant (ttest, t=1, p<0.001), but it leads to a decrease in performance during the next phases, test1 and test2, in which there is no positively biased feedback (see Figure 3.1).

A more constant behavior can be seen in the second day (see Figure 3.3), in which encouraging feedback was not introduced. The average scores decreased slightly over the phases. During baseline, participants answered correctly to 56.2% (SD=16.2) of the questions. In the second phase, the average level of correct answers was 55.6% (SD=12.6), while during the last phase the average score was only 54% (SD=14.8).

The overall performance is around 10% higher compared to the one during the first day.

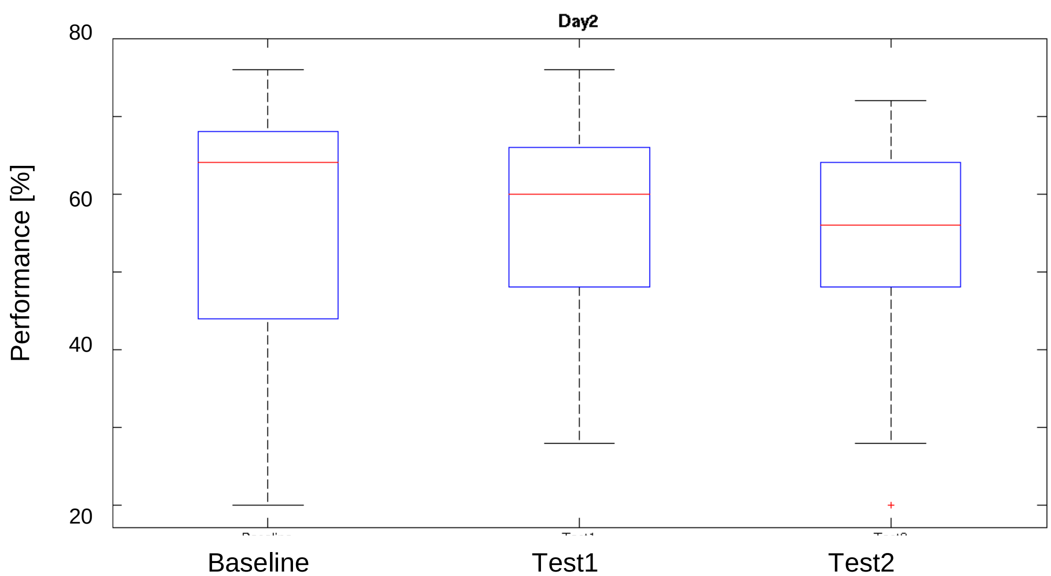


Figure 3.3. Overall performance during the second day of the experiment

In order to better see the effect of our intervention (light and encouraging feedback) we split the last two phases according to the corresponding conditions, congruent-first and incongruent-first (see Figure 3.4).

During the control condition the variance of the performance scores was very large for most of the phases, except for the third one. In the baseline, the average performance score was 46% (SD=14). During association, the scores were slightly decreasing, the average performance was 40.5% (SD=15). Next, during the third phase, the scores were decreasing even further and the variance of the scores is significantly smaller; the average score is 38% (SD=2.3). In the last phase, most of the participants increased their levels of performance, the average performance was 51% (SD=14.4), which is the highest level of performance over all phases of the control condition.

The congruent-first condition presented a “zig-zag” trend in the levels of performance over phases, with both positive and negative slopes. During the first phase, the average performance score was 45.5% (SD=12.5). Then, the association presented a slight increase in performance, with an average score of 52% (SD=8.8).

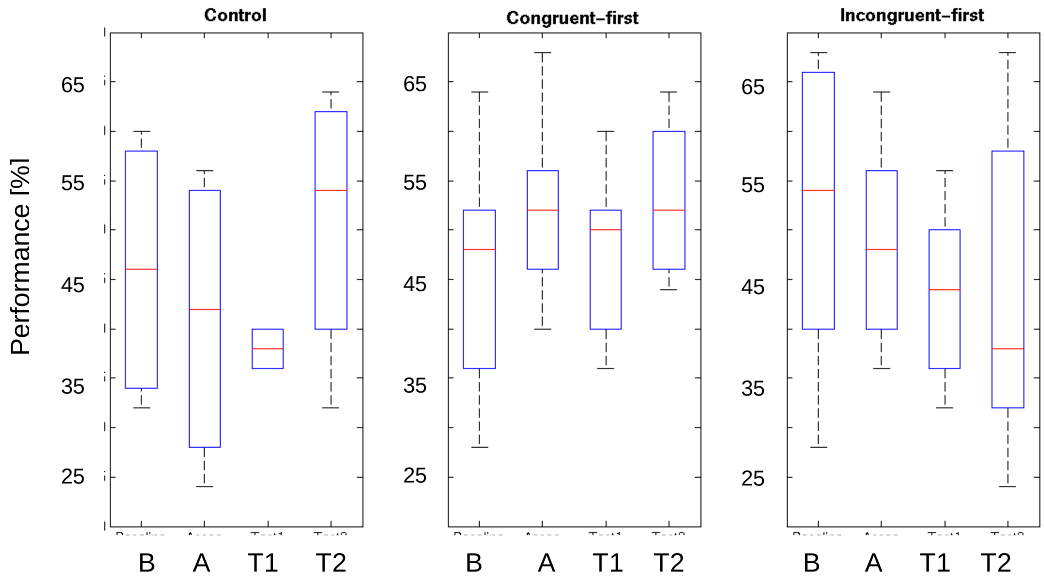


Figure 3.4. Box-plots of the performance scores during the first day in each of the conditions.

The third phase, congruent, had the average performance, 46.8% (SD=8) a bit higher than the baseline. The fourth phase presented higher levels of performance, average score was 53% (SD=7.9) of correct answers. There was no significant difference between the phases of the congruent-first condition.

The incongruent-first condition presented a continuous decrease in performance over the phases. The baseline phase presented the average score of performance of 52% (SD=15.7). This is the highest averaged value from all the phases of this condition, but is not significantly higher than the rest. The variance is also very large. During the association, the variance of the performance scores was smaller compared to the baseline, the average score of performance was 48.5% (SD=9.7). The third phase, incongruent, presented the average performance score of 43.5% (SD=8.7). The last phase, congruent, has the largest variance in performance levels, the average level of performance was the same (43.5% (SD=16.1)) as during the previous phase, incongruent, but the variance was larger.

In the second day of the experiment, the task was similar to the one in the first day. The association phase was missing from the structure of the second day of experiment.

Figure 3.5 presents the performance over the phases corresponding to the three conditions: control, congruent-first, and incongruent-first.

The first subplot, presents the control condition. The variance of the performance scores in this condition is larger compared to the rest of the conditions. Baseline presented the average performance score of 46% (SD=23.7). During the next phase, the average performance score remained the same (46%), but the variance decreased (SD=12). During the third phase the average performance was 44%. The variance of scores during this phase (SD=19.9) was very similar with the first phase, baseline.

The second subplot presents the performance levels during congruent-first condition. The baseline had the average performance score of 60% (SD=11.5). The second phase, congruent, had larger variance (SD=15.9) and similar score of average performance, 58%. The last phase, incongruent, had the average performance level of 59.5% and similar distribution of performance scores (SD=14.1) as the other phases. Compared to the test1 (congruent), the variance is slightly diminished during test2 (incongruent), but the results do not presents any significant difference.

The last subplot presents the performance levels during incongruent-first condition. This condition presents a decreasing trend over the phases, similar with the one during the first day. The baseline had the largest variance in performance scores (SD=16.1) and the average performance of 57.5%, also the highest median value from this condition. The second phase, incongruent, presents smaller variance (SD=7.4) and a similar averaged score (58%) compared to the baseline. The last phase, congruent, has smaller variance from (SD=6.2) and median score of 53.5%.

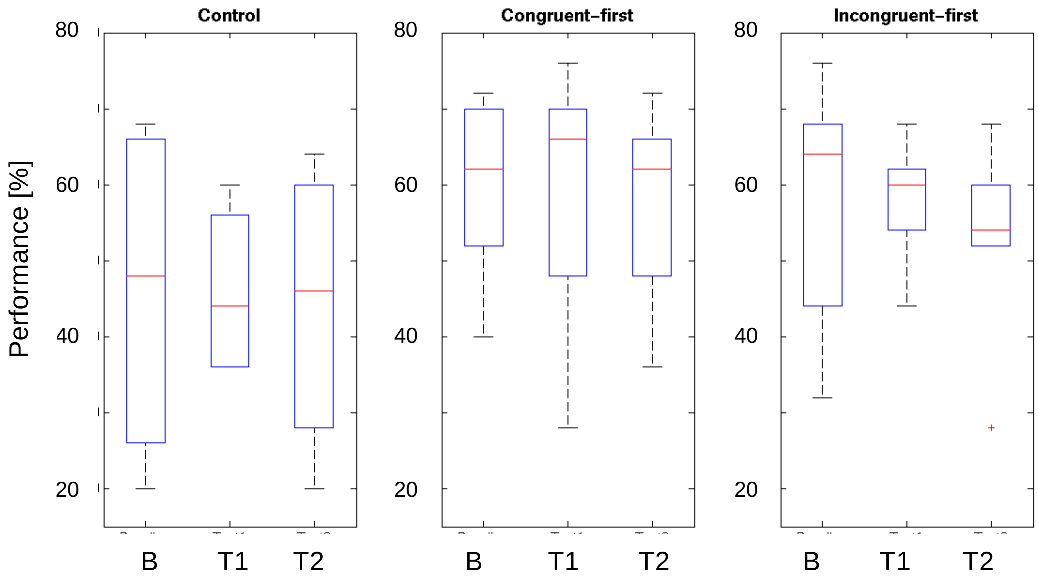


Figure 3.5. Box-plots of the performance scores during the second day in each of the conditions.

A more detailed preview, at the participant's performance level, is presented in Figure 3.6. We can distinguish between the levels of performance during both days. The bars represent the phases from the performance evolution of each participant and are presented in the following order: baseline, association, incongruent and congruent, in the first day graphs. During the second day, the order is the same, without the association, baseline, incongruent, congruent.

The representations in Figure 3.6 respect the following correspondence:

	Congruent first green	Incongruent first orange	Incongruent first green	Congruent first orange
Control	Group 112	Group 121	Group 212	Group 221
▬ baseline	▬ baseline	▬ baseline	▬ baseline	▬ baseline
▬ association	▬ association	▬ association	▬ association	▬ association
▬ test1	▬ incongruent	▬ incongruent	▬ incongruent	▬ incongruent
▬ test2	▬ congruent	▬ congruent	▬ congruent	▬ congruent

Table 3.1.Order of the phases in each group

The representations during the second day are the same as in Table 3.1, excluding the association.

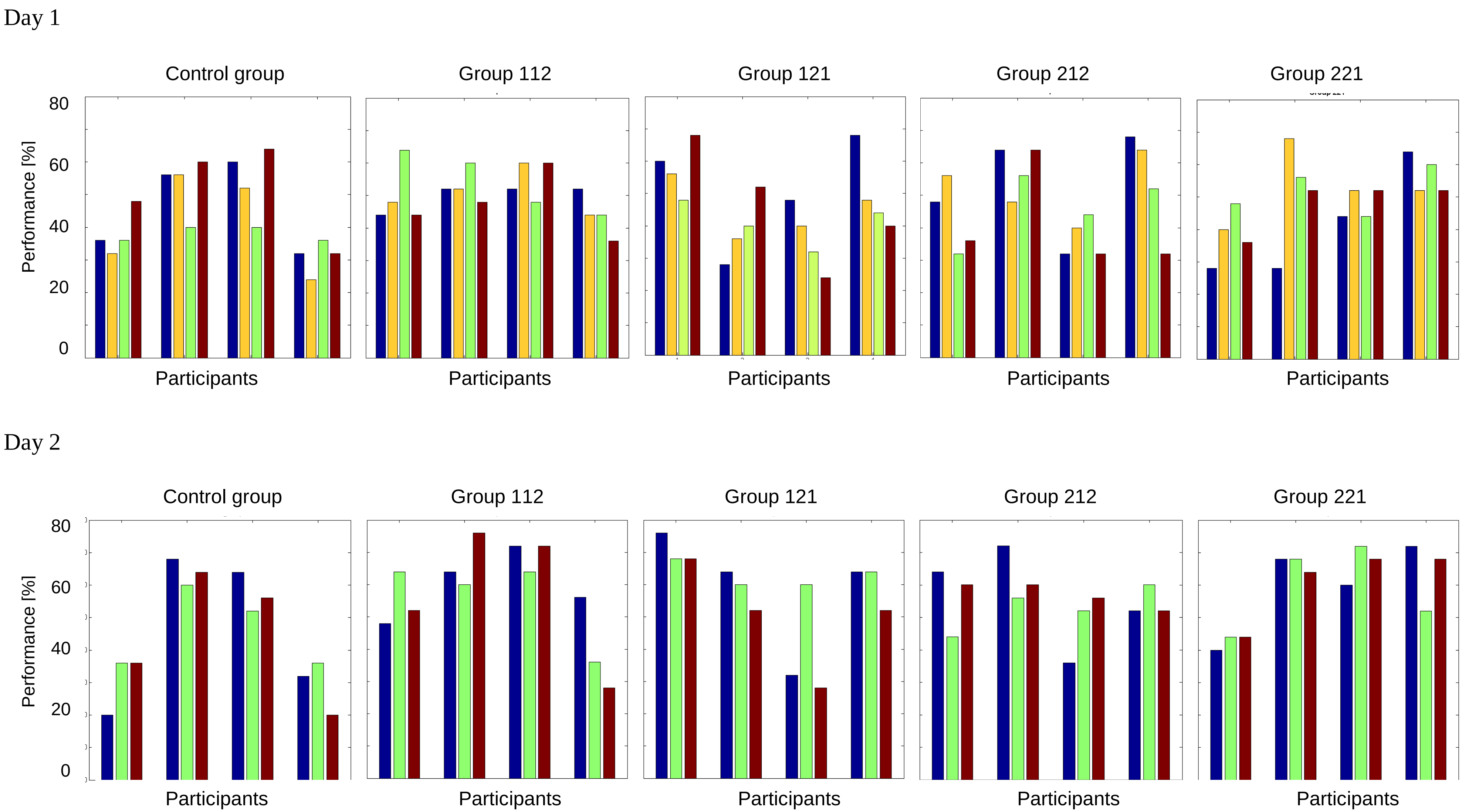


Figure 3.6. Performance scores for each participant in both days

3.1.2 Comparison with the previous experiment

For a better understanding, we decided to compare the obtained results with the ones of the previous experiment, see Section 1.3 and [48], in terms of a between-subjects analysis.

In the previous experiment, we did a similar study in which we measured cognitive performance in a Trivia test, when the participants performed the task under the influence of light and encouraging feedback. The performance scores are reported in Figure 1.5.

As in the previous study the intervention was presented both during association and test phase, we decided to split, for comparison reasons, the current association phase in two parts (see Figure 3.7).

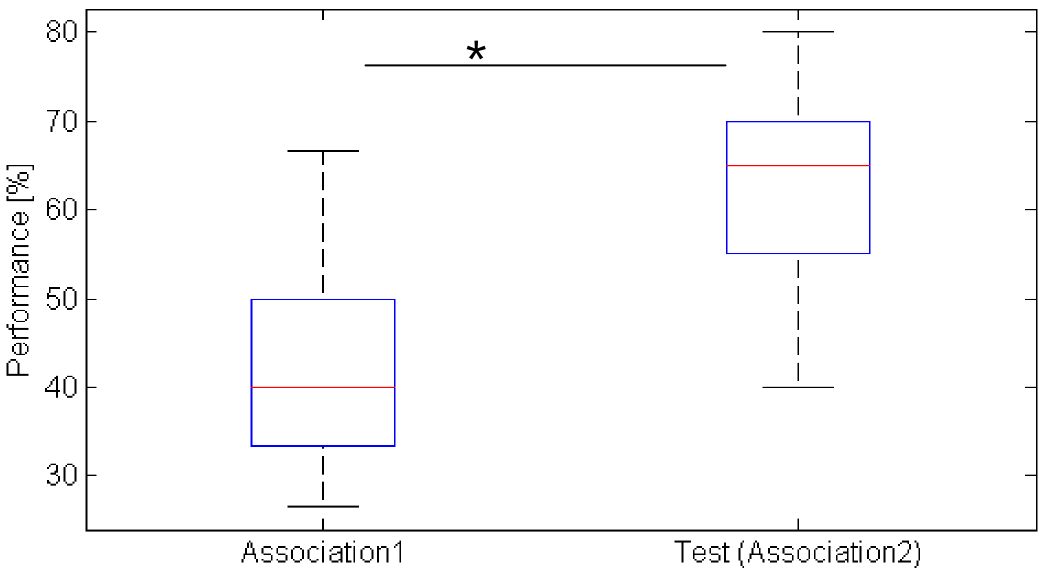


Figure 3.7. Splitting the association phase in order to compare the results in performance

We assume that in the first part we establish the association and the second part represents the testing.

The average performance score of the newly obtained association was 41.7% (SD=11.5), while the new testing phase had a very high the average score of 63.1% (SD=13), compared to the other phase. This difference was significant (ttest, t=1, p<0.001) and presented similar trend compared to the congruent condition of the previous experiment. Because of the experimental design, we however cannot replicate the incongruent condition of the previous experiment.

When analyzing the performance, we should also consider the influence of other factors, like:

a. Difference in population's cognitive level – We explored the influence of this factor by comparing the levels of performance during the baseline phase of both experiments, see Figure 3.8;

In Figure 3.8 the first box-plot represents the performance during the baseline phase of the previous experiment. The average performance score is between 41.7% (SD=10.3). The second box-plot corresponds to the performance during the baseline phase of the current experiment. The second experiment presents higher variance (SD=17.5) than the previous experiment. The average performance score is 48.2%.

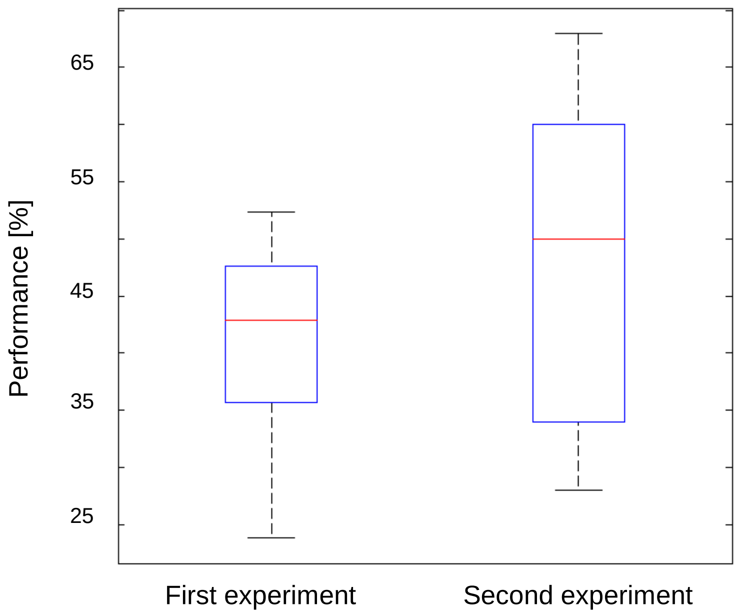


Figure 3.8. Average performance scores for the groups of participants in both experiments

b. Difficulty of the question sets – We decided to investigate the influence of this factor as, during both experiments three sets of questions were the same, see Figure 3.9.

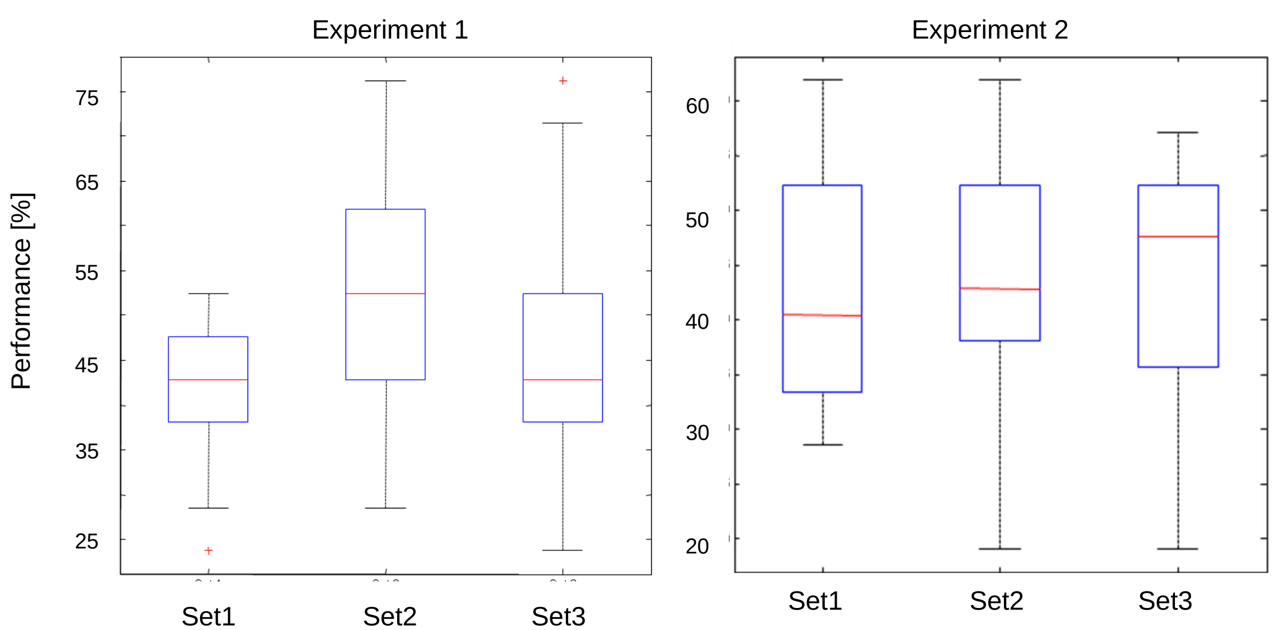


Figure 3.9. Comparison of the same sets of questions in both experiments

Figure 3.9 presents in the first subplot the performance level registered in the first experiment. The second subplot presents the performance levels over the same three sets, in the second experiment.

During the first experiment, in Set1, the average performance was 41.2% (SD=10.3), with an outlier indicating a level of performance of 24%. During Set2 the average performance level was 53% (SD=21.6). The average performance score registered during Set3 was 44% (SD=21.7) with an outlier indicating a level of performance of 77%.

In the second experiment, during Set1 the average level of performance was 42% (SD=11.3). Set2 had the averaged level of performance of 38.1% (SD=20.3). During Set3 the average level of performance was 41.7% (SD=10.2).

The results present no significant difference in the difficulty between the sets in none of the experiments.

3.1.3 Effect of previous feedback on next answers

Figure 3.10 presents the sequence of answers and the influence of the previous feedback on the current response. Each color corresponds to a certain sequence of answers (see Table 3.2).

Sequence		Color
Previous feedback	Actual performance	
Incorrect	Incorrect	(dark blue)
Incorrect	Correct	(cyan)
Correct	Incorrect	(yellow)
Correct	Correct	(dark red)

Table 3.2. Classification of types of sequences with the corresponding color

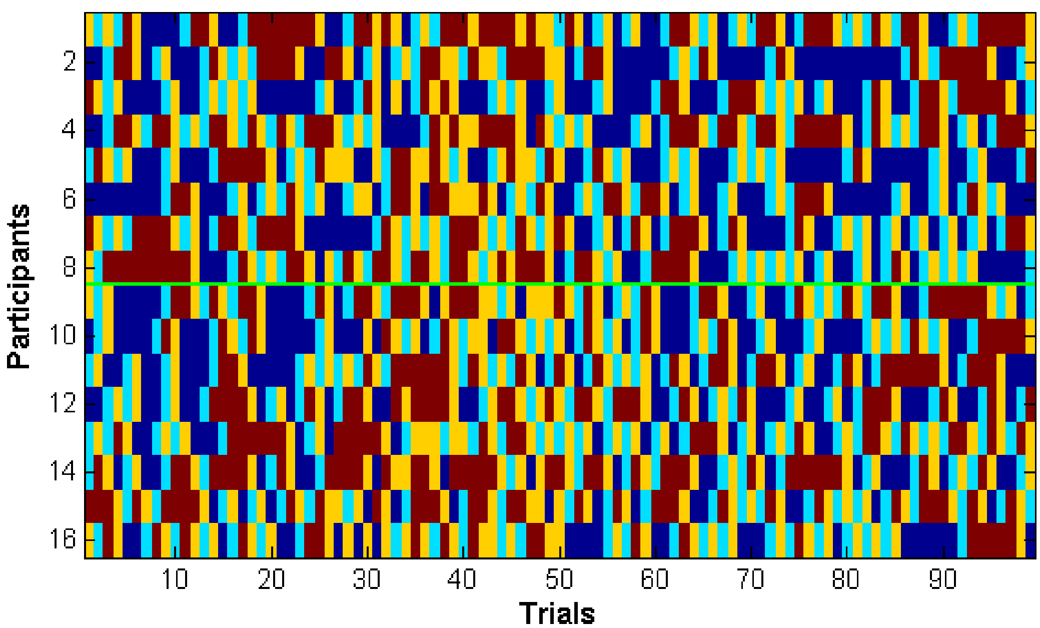


Figure 3.10. Sequence of answers for each participant

In Figure 3.10 the first half (above the green line) the participants belonging to the incongruent first condition, in the second half (below the green line) there are presented the participants from the congruent first condition.

Figure 3.10 presents different sequences of feedback over the task's performance. During the association, where the positively biased feedback was introduced, we can see longer sequences of yellow, corresponding to incorrectly answered trials precede by a correct feedback.

Figure 3.11 presents the box-plots for the following probabilities:

$$P(corr \mid corr\_prev) = \frac{P(corr\_prev, corr)}{P(corr\_prev)} = \frac{sum(red)}{sum(yellow) + sum(red)} \tag{5}$$

$$P(corr \mid incorr\_prev) = \frac{P(incorr\_prev, corr)}{P(incorr\_prev)} = \frac{sum(cyan)}{sum(blue) + sum(cyan)} \tag{6}$$

$$P(incorr \mid corr\_prev) = \frac{P(corr\_prev, incorr)}{P(corr\_prev)} = \frac{sum(yellow)}{sum(red) + sum(yellow)} \tag{7}$$

$$P(incorr \mid incorr\_prev) = \frac{P(incorr\_prev, incorr)}{P(incorr\_prev)} = \frac{sum(blue)}{sum(blue) + sum(cyan)} \tag{8}$$

$$P(correct) = sum(red) + sum(cyan) \tag{9}$$

$$P(incorrect) = sum(blue) + sum(yellow) \tag{10}$$

(5) represents the conditional probability of having a correct answer when the previous feedback was also correct.

(6) represents the conditional probability of having a correct answer when the previous feedback was incorrect.

(7) represents the conditional probability of having an incorrect answer when the previous feedback was correct.

(8) represents the conditional probability of having an incorrect answer when the previous feedback was incorrect.

(9) represents the probability of having a correct answer regardless if the previous feedback was correct or incorrect.

(10) represents the probability of having an incorrect answer regardless if the previous feedback was correct or incorrect.

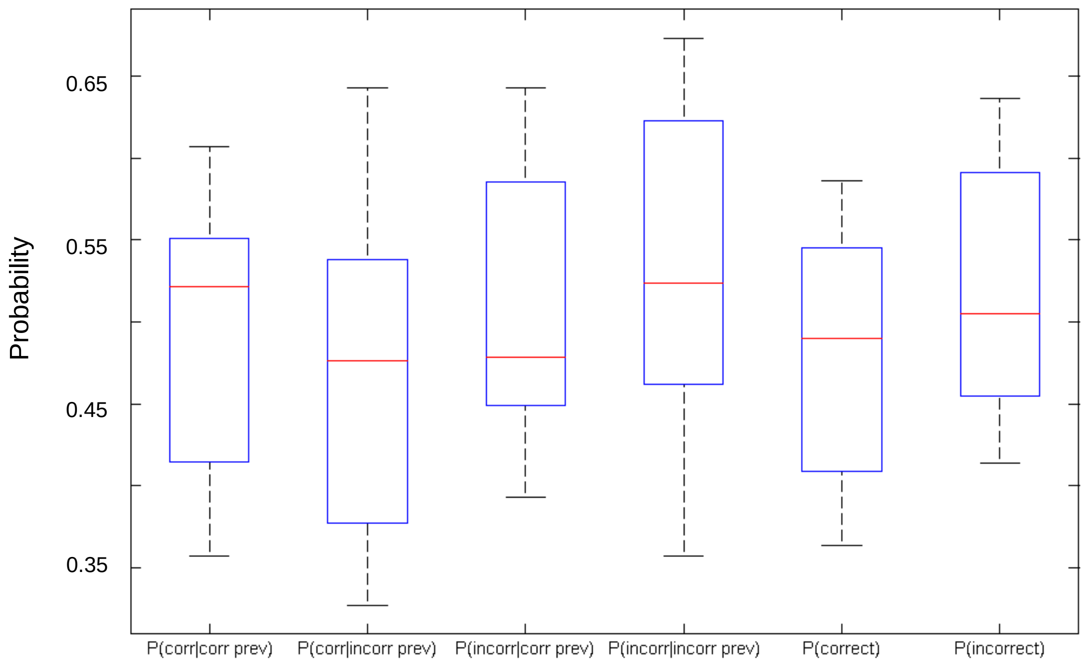


Figure 3.11. Box-plot representing probabilities and conditional probabilities

In Figure 3.11, there is no significant difference between the evaluated probabilities. Nevertheless, we can observe that the probabilities P(corr|corr prev) and P(incorr|incorr prev) have higher median scores (52%) compared to the P(corr|incorr prev) and P(incorr|corr prev), (47%).

3.1.4 Effect of light priming and encouraging feedback on reaction time

Overall reaction time was measured as the duration in seconds from the onset of the question until the participants pressed a key, corresponding to one of the four possible answers. Figure 3.12 presents the average reaction time for the correctly and incorrectly answered trials during the first day of the experiment. The minimum average reaction time for the correct answers is 6 seconds, while the maximum is 13 seconds, with a median value of 9.5 seconds, which is a third out of the total time available for answering the question (30 seconds). The incorrectly answered trials present the same interval for the averaged reaction time, between 6 and 13 seconds, but the median value is lower, 8 seconds.

Figure 3.12. Average reaction time (RT) for correctly/incorrectly answered trials during the first day of the experiment

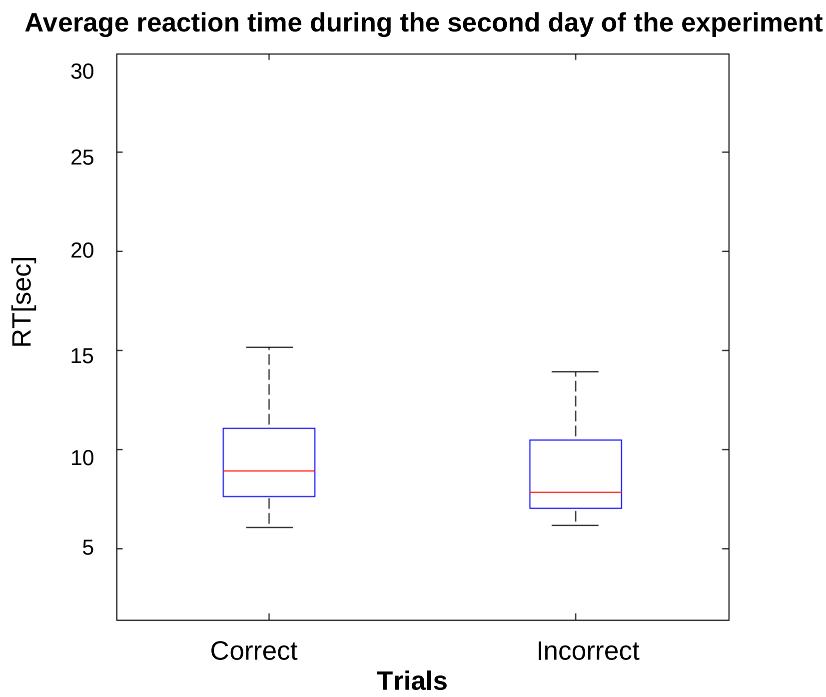


Figure 3.13. Average reaction time (RT) for correctly/incorrectly answered trials during the second day of the experiment

Figure 3.13 presents the average reaction time for the correctly and incorrectly answered trials during the second day of the experiment. The intervals for the average reaction time are very similar with the ones during the first day of the experiment. The median value of the averaged reaction time for the correct answers is 9 seconds and for the incorrect answers is 8 seconds. The results present no statistical significance neither between conditions, nor days.

3.2 Effect of augmentation methods on motivation

During this experiment we used only 2 subscales of the Intrinsic Motivation questionnaire: Perceived competence and Effort/Importance. This subsection presents the scores of the subscales in correlation with the performance.

Figure 3.14 presents the trend in performance, explained as the number of correct answers, of the participants from the control group and the trends of 2 subscales of the Intrinsic Motivation questionnaire, Effort/ Importance and Perceived competence. This analysis includes 4 participants.

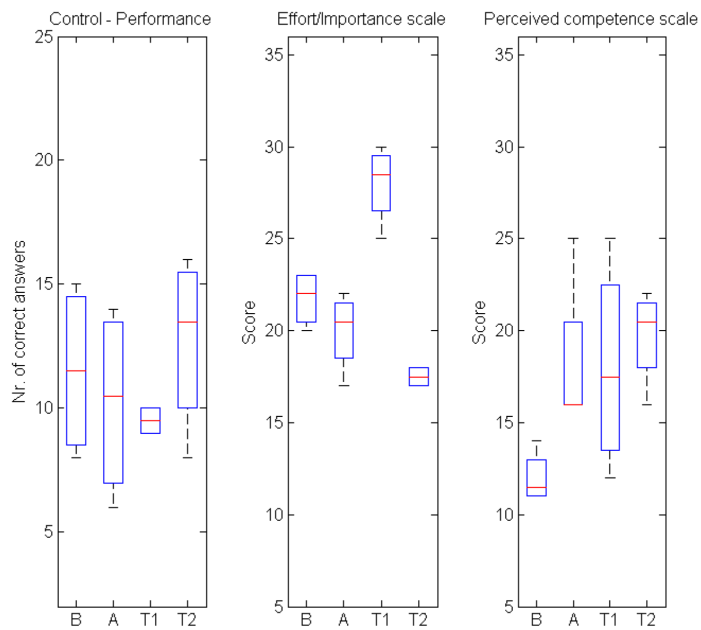


Figure 3.14.The number of correct answers in the control condition during the first day of the experiment and the corresponding scores for the Effort/Importance scale and Perceived competence scale

In Figure 3.14, the first subplot presents the number of correct answers over the phases of the control condition. During the baseline, the average number of correct answers was 12 (SD=3). During the association, the average number of correct answers slightly decreased, reaching a value of 11 (SD=3). The third phase had very small variance (SD=1.5); the participants answered correctly to an average of 9.5 questions, the smallest number of this condition. During the fourth phase, the number of correct answers increased compared to the third phase, reaching an average of 13 (SD=3), which is the highest average value of the condition.

The Effort/Importance scale presents fluctuating median values of the scores over the phases. The variances of the phases are partly overlapping. The minimum score over the phases is 17 and the maximum, 30, with median values of 19, 21, 20 and 22. The Perceived competence scale has the same distribution of scores over the phases as the performance. During baseline the minimum score is 11 and the maximum 25, having a median value of 19. During association, the score decreases to a minimum of 11 and a maximum of 16, and a median value of 15.5, corresponding to a similar decrease of the number of correct answers. During the third phase, the minimum score is 12 and the maximum is 20, with a median value of 14. The last phase has distribution of scores overlapping the first phase's scores. Minimum score is 14; maximum is 20 and the median value, 20.5.

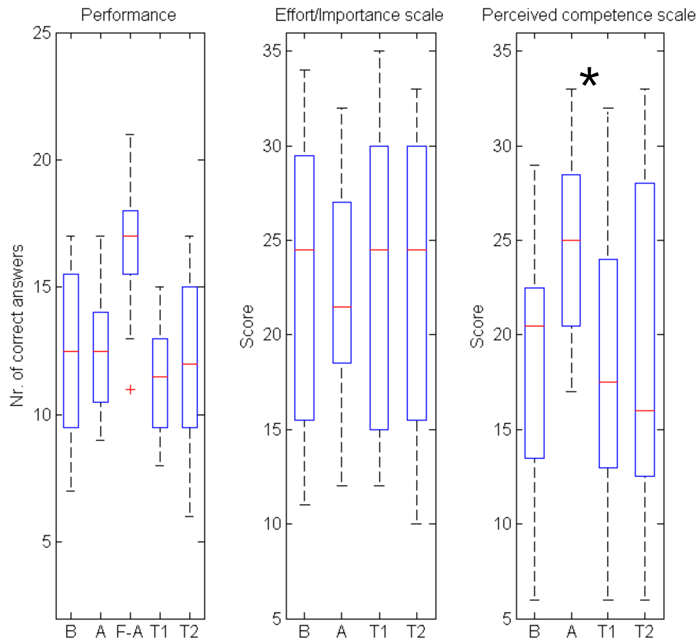


Figure 3.15. The number of correct answers in the intervention conditions during the first day of the experiment and the corresponding scores for the Effort/Importance scale and Perceived competence scale

Figure 3.15 presents the overall results of the Trivia quiz and the results of the questionnaire for participants from both congruent-first and incongruent-first. One observation is represented by the correlation between performance and perceived competence. The average performance score over the phases was 50% (SD=11.2), while the positively biased level of performance was 70% (SD=8.9). The Effort/Importance scale presented score in a very large variance and with a similar average value. The Perceived competence scale presented a significant difference between the second and the third phase's scores. A similar decreasing trend was presented in the performance subplot.

In Figure 3.16 the first subplot has 5 box-plots. The first two and the last two correspond to the phases of the congruent-first condition. The third, the middle one, represents the number of encouraging (truly correct and positively biased) messages during the association phase. The reason for including this box-plot is its influence on the questionnaire scores. The second and the third subplots represent the scores for the two questionnaire's subscales. This analysis includes 8 participants.

The first subplot presents the number of correct answers during the congruent-first condition of the first day of experiment. The average values of the correct answers over the phases present a fluctuating distribution. During baseline, the average number of correct answers was 11 (SD=4). The association presents the average number of correct answers as being 12 (SD=3). During the same phase, due to the encouraging feedback, the encouraging messages average was 18 (SD=1), with outliers at 14 and 19.

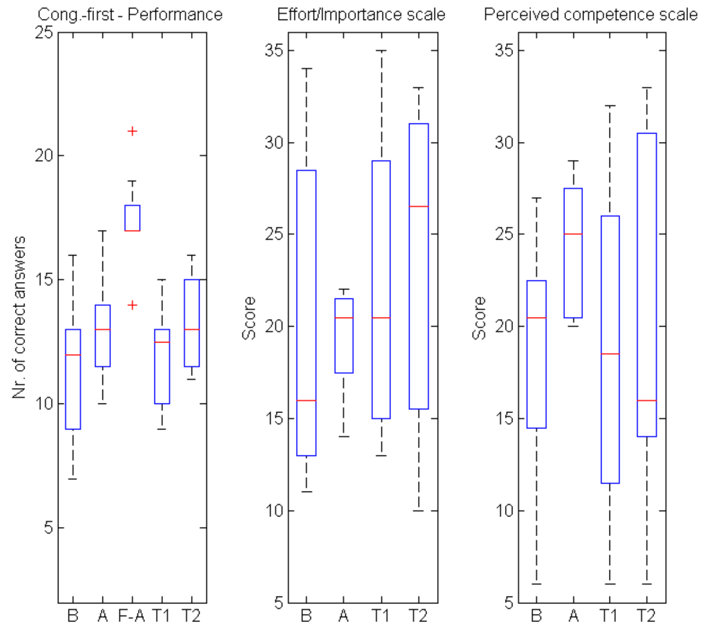


Figure 3.16. The number of correct answers in congruent-first condition during the first day of the experiment and the corresponding scores for the Effort/Importance scale and Perceived competence scale

During the third phase, congruent, the average number of correct answers was 12 (SD=3). The last phase, presented the average value of 13 (SD=3).

The Effort/ Importance scale presents overlapping distributions of scores over the phases, with a minimum score of 10, a maximum of 35 and median values of 16, 20, 20 and 26. During the association the variance of the scores is less large than during the rest of the phases. The minimum score is 14 and the maximum is 21.The Perceived competence scale presents a very large distribution of scores. During the baseline, the minimum score is 6 and the maximum 27, with a median value of 20.5. The scores during association are higher, reaching a minimum of 20 and a maximum of 29, with a median value of 25. During the third phase, congruent, the scores decrease to a minimum of 6 and a maximum of 32, and a median value of 18. The last phase presents similar intervals for the score, minimum of 5 and maximum of 33, but the median value diminishes to 15.5.

Similar to Figure 3.16, Figure 3.17 presents 3 subplots. The first subplot has 5 box-plots. The first two and the last two correspond to the phases of the incongruent-first condition. The third, the middle one, represents the number of encouraging (truly correct and positively biased) answers during the association phase. The reason for including this box-plot is its influence on the questionnaire scores. The second and the third subplots represent the scores on the questionnaire's subscales. This analysis includes 8 participants.

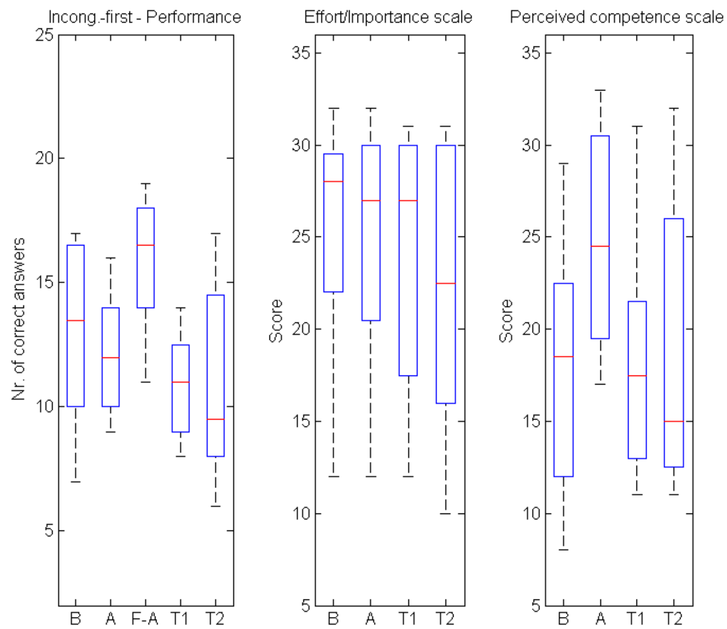


Figure 3.17. The number of correct answers in incongruent-first condition during the first day of the experiment and the corresponding scores for the Effort/Importance scale and Perceived competence scale

Incongruent-first condition presents in terms of correct answer a continuous decrease over the phases. The baseline phase presents the average number of correct answers as being 13 (SD=5). This is the highest average value from all the phases of this condition. During the association, the variance of the number of correct answers was smaller compared to the baseline (SD=3). The average number of correct answers was 1w. During the same phase, due to encouraging feedback, the biased number of correct answers was increased. The encouraging messages average was 15 (SD=4). The third phase, incongruent, presented the average number of correct answers as being 11 (SD=3). Next, the last phase, the congruent, had the largest variance in number of correct answers (SD=6). The average number was 10.5.

The Effort/Importance scale presents similar distribution of scores, with large variances. The minimum score is 10 and the maximum is 32, with decreasing median scores of 28, 27, 27 and 22. Perceived competence scale presents during baseline a minimum score of 8 and a maximum score of 29, with a median value of 19. During the association, the scores increase, to a minimum of 17 and a maximum of 30, with a median value of 23. The third phase, incongruent, presents a decrease of scores reaching a minimum of 11 and a maximum of 31, with a median value of 18. The last phase, congruent, presents a similar interval of scores as the incongruent, between 11 and 32, but with an even less high median value 15.

After running a statistical test we found that the score of the Perceived competence scale during the third phase is significantly smaller than the score during the second phase (t=1, p=0.05).

The next three figures, Figure 3.18, Figure 3.19 and Figure 3.20 present the results of the Trivia test during the second day. The expectations for these results were to be at least as high as the ones during the first day of the experiment.

In the second day of the experiment the association phase was missing. The reason for this absence was to test the prolonged effects of the intervention introduced in the first day.

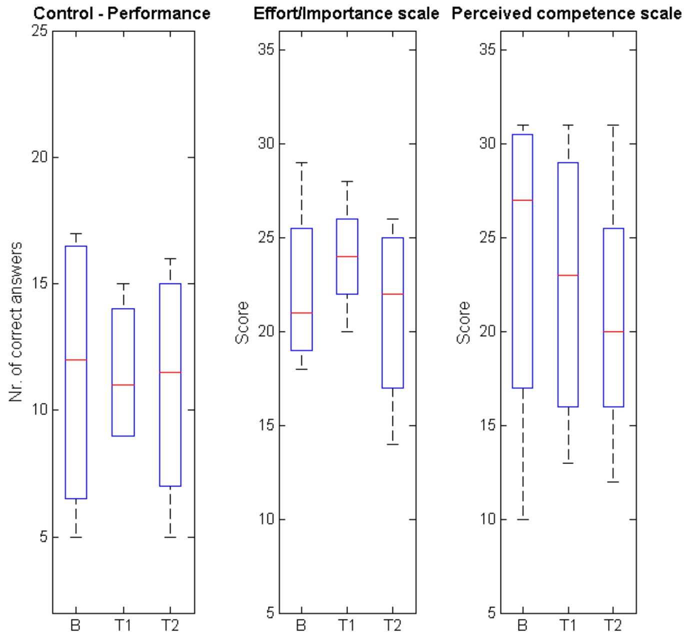


Figure 3.18.The number of correct answers in the control condition during the second day of the experiment and the corresponding scores for the Effort/Importance scale and Perceived competence scale

In Figure 3.18, the first subplot presents the number of correct answers over the phases of the control condition. This analysis included the same 4 participants as in the first day.

During the baseline, the average number of correct answers was 11 (SD=6). During the second phase, the variance of the number of correct answers decreased (SD=4), the average value remained constant. The third phase has similar variance with the first phase (SD=6); the participants gave an average number of 10.5 correct answers.

The Effort/Importance scale presents during baseline a minimum score of 18 and a maximum of 29, with a median value of 21. The second phase has less variance compared to the first one, scores between 20 and 28, and a higher median score of 24. The Perceived competence scale presents similar distribution of scores over the phases. The median scores show a decreasing trend. The interval of the scores is 10 to 31 and the median values are 27, 23 and 20.

The first subplot in Figure 3.19 presents the number of correct answers during the congruent-first condition of the second day of experiment. During baseline, the average number of correct answers was 14 (SD=4). The second phase, congruent, presented the average number of correct answers as being 13, with a slightly higher variance (SD=6). During the third phase, incongruent, the average number of correct answers was 13.5 (SD=5).

The Effort/Importance scale presents fluctuating scores over the phases. During baseline, the minimum score is 10 and the maximum is 33, with a median score of 24. During congruent phase, the variance of the scores is smaller; the minimum score is 15 and the maximum 21, but the median score is lower than the previous one, having a value of 18. Incongruent phase presents a minimum score of 13 and maximum of 33, with a median score of 27. Perceived competence scale presents similar distribution and large variance of scores over the phases of the congruent-first condition. The interval of scores is between 6 and 31, with median values of 25, 22.5 and 24.

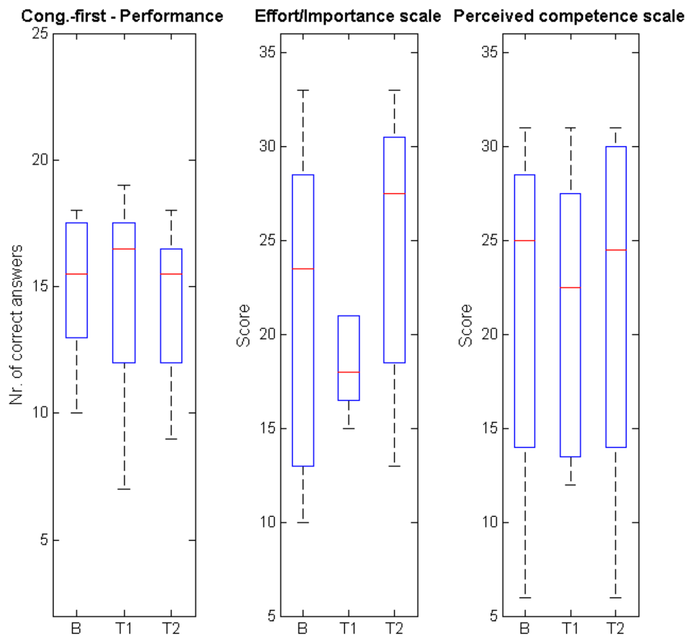


Figure 3.19. The number of correct answers in congruent-first condition during the second day of the experiment and the corresponding scores for the Effort/Importance scale and Perceived competence scale

As in the first day of experiment, incongruent-first condition presents in terms of correct answer a continuous decrease over the phases, see Figure 3.20. The baseline phase presented the average number of correct answers as being 13.5 (SD=5). This is the highest median value from all the phases of this condition. During the second phase, incongruent, the variance of the number of correct answers was smaller compared to the baseline (SD=3). The average number of correct answers was 14. The third phase, congruent, presented similar variance as the incongruent (SD=2). The average number of correct answers was 15.

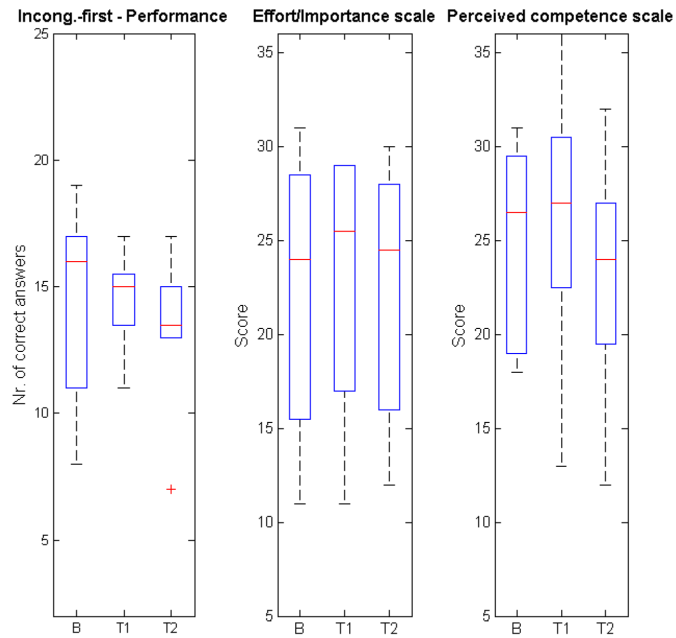


Figure 3.20. The number of correct answers in incongruent-first condition during the second day of the experiment and the corresponding scores for the Effort/Importance scale and Perceived competence scale

The Effort/Importance scale presents similar distribution of scores and large variances. The minimum score is 11 and the maximum is 32, with fluctuating median scores of 24, 25 and 24.5. Perceived competence scale presents during baseline a minimum score of 17 and a maximum score of 31, with a median value of 26. During the incongruent phase, the scores have larger variance, with a minimum of 13 and a maximum of 36, with a median value of 26.5. The third phase, congruent, presents a decrease of scores reaching a minimum of 12 and a maximum of 32, with a median value of 24.

3.3 ERP analysis related to encouraging feedback

In cognitive psychology brain activity monitoring is used for a deeper understanding of the results obtained from the analysis of behavioral data. In this subsection we are presenting the findings according to the event related potentials (ERPs) investigation.

3.3.1 Grand average ERPs

The signals represented in Figure 3.21 (a, b, c, d) respect the following color association.

Color	Type of feedback
red line	incorrect
blue line	correct
green line	positively biased
black line	diff(correct, incorrect)

Table 3.3. Types of feedback and the associated color in Figure 31 (a,b,c,d)

The vertical dashed line at 0 represents the onset of the feedback.

Figure 3.21 presents the grand average for ERPs 500 milliseconds before the onset of the feedback and 1000 milliseconds after the onset of the feedback. The grand averages are presented in 4 locations: Fz, Cz, Pz and Oz. The figure presents 3 different signals (see Table 8) corresponding to the delivered feedback and one difference between the correctly and incorrectly answered trials. Figure 3.21(a) presents a clear peak, around 250-300 milliseconds, representing the difference between the above mentioned signals. This peak is also known as feedback negativity (see Section 1.4 and [50]). This component can be detected also in the rest of the figures, b, c, d, but it does not have the same magnitude and it is not significant.

For the signal trial analysis of the ERP data, the interested reader can access Appendix C1.

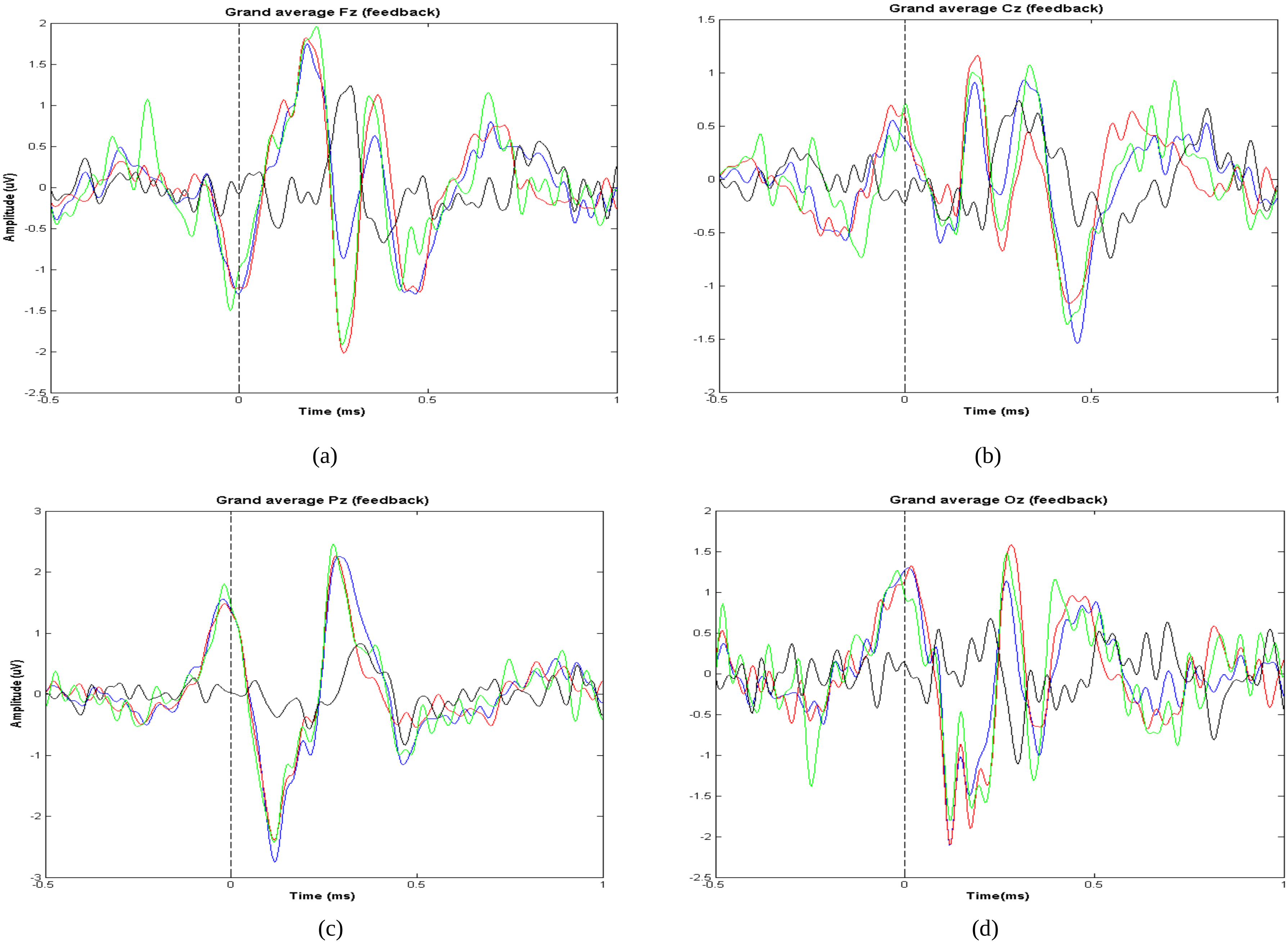


Figure 3.21.Grand average across all participants in a window showing the onset of the feedback on channel Fz (a), Cz (b), Pz (c), Oz (d)

4. Discussion and Conclusions

The research questions that we addressed at the beginning focused on: 1) how cognitive performance is influenced by light priming, (2) what is the effect of light priming and encouraging feedback on participants' motivation and to how is it related to cognitive performance and (3) what are the patterns in neural response that correlate with encouraging feedback.

4.1 Effects of augmentation methods on cognitive performance

During the first day of the experiment, the overall performance presented similar values. The third phase presented a smaller variance, having values between 32% and 60% - which might be due to the higher scores in performance displayed on the screen, during association, as a result of the encouraging feedback.

Second day presents 10% higher results than the first day. We assume the cause of this behavior is the learning process of the task itself. Even though, Trivia test is a general knowledge test with different questions, the participants might have got familiar with the types of questions presented during the first day of the experiment.

Comparing the overall levels of performance in both days (see Figure 3.1 and Figure 3.3) we can conclude that during the second day the participants performed better under the effect of our intervention, regardless of the condition (congruent-first or incongruent-first), while during the control condition, their performance remain constant, sometimes even decreased.

The results suggest that the trend in performance is mostly influenced by the presence of the encouraging feedback.

The design of this experiment allowed us to replicate partly the findings of the previous experiment. In the previous experiment, the performance during the baseline is similar in all the conditions (43%), which means that the participants were fairly equal distributed across the three groups. The performance in the third phase has lower values in the control (43%) and incongruent conditions (39%), compared to the same phase during congruent condition.

The performance during the test phase of the congruent group is higher than the one in the incongruent and control groups, which indicates the effects of light priming. By comparing these results with the control condition, we can also say that, the improvement in the congruent group is caused by both the effects of light and positively biased feedback.

After splitting the association phase, in order to replicate previous findings, the results were significant (t=1, p=0.05) and present similar trend as the congruent condition of the previous experiment. Because of experimental design we cannot simulate the incongruent condition of the previous experiment.

As potential factors that could influence our results, we considered the population knowledge level and the difficulty of the sets. The populations for each experiment have comparable knowledge level. The questions were equally distributed over the sets in terms of difficulty.

Summarizing all the results that we have so far, brings us to the conclusion that there is no big influence of light, but the encouraging feedback induces some important effects.

The feedback gradually becomes the most salient factor in the process of modulating cognitive performance.

4.2 Effect of augmentation methods on motivation

Considering our second research questions, what is the effect of light priming and encouraging feedback on participants' motivation and to how is it related to cognitive performance, we analyzed the questionnaire's features, like Effort/Importance scale and Perceived competence scale which act as mediators of cognitive performance. The behavioral results showed that during the third phase, of the control condition, the participants answered correctly to fewer questions (a median number of correct answers of 9.5) than during the rest of the phases (median number of correct answers between 10.5 and 13). It should be considered that these participants, the control group, were under no effect of intervention (light stimulation and encouraging feedback).

The trend in performance is replicated by the scores in the perceived competence scale. The Effort/Importance scale suggests that it was equally important for the participants to perform well during all the phases.

If we compare the trends in performance in the control condition and during the other two conditions (congruent-first and incongruent-first), taken together, we can conclude that when the participants feel less motivated, due to the absence of encouraging feedback, they perform worse. In the control condition, during the last phase their motivation increased leading to an increase in performance. Maybe they associate the light with a negative performance.

Alike the control group, the number of correct answers during the congruent phase of the congruent-first condition is smaller than during the rest of the phases. The Effort/Importance scale presents increasing scores, even though not significant because of the large variances, over the phases. This result suggests that for the participants it was important to perform well during the entire experiment, regardless of the intervention. When looking at the difference between the encouraging messages during association and the performance (represented by the number of correct answers) during congruent phase, it can be seen that the participants did not perform as high without positively biased feedback. The same difference of scores between association and congruent can be seen in the Perceived competence scale (even though not significant, p = 0.1), which suggests that the positive reinforcement is a modulator of perceived competence, which indirectly influences performance.

During the incongruent-first condition, the number of correct answers has a decreasing trend over the phases of the experiment. The Effort/Importance scores are not affected by the encouraging messages. The influence of the positively biased feedback is noticeable in the Perceived competence scores, in which during association, the score is higher (the score equals 23) and decreases during the third phase (the score is 18). A statistical test (ttest) was run in order to see how significant this difference is. The result was not significant (p = 0.08). This result might have been significant if the population would have been larger.

In the control condition of the second day of the experiment the box-plots representing the numbers of correct answers during each phase do not present any significant difference. The scores on the Effort/Importance scale are not very different either. It only seems that when the performance was lower, the importance of the task was higher. The Perceived competence levels decreases during the task. This analysis included the same 4 participants as in the first day.

The congruent-first group presents similar performance over the phases. There is no significant difference between phases, only the median red lines, suggest that during the congruent phase most of the participants performed slightly better.

The Effort/Importance scale presents a very low level for the scores during congruent phase, which means that the participants were not putting a lot of energy into the task. In spite of this result, during the next phase, the scores increased significantly (p =0.04), suggesting that the participants become motivated to perform well again. In the Perceived competence scale the scores have very similar levels along the phases (around 24%).

During the incongruent-first condition, the performance, expressed as the number of correct answers, presents a decreasing trend during the phases. The Effort/Importance scale shows no difference between phase scores, suggesting that it was equally important for the participants to perform well during all the phases of the experiment. In the Perceived competence scale, the last phase presents a slowly decreasing level, which is explained by the poor performance during the last phase.

During the second day of the experiment, the scores of the Perceived competence scale were higher than during the first day, which suggests that the participants were more self confident.

4.3 Patterns in neural response that correlate with encouraging feedback

Our third research question was to investigate how to assess cognitive performance with brain responses.

The feedback negativity is a component of the event-related brain potential that is elicited by feedback stimuli associated with unfavorable outcomes. We detected this feature, represented as the difference between correctly and incorrectly answered trials, at 250-300ms after the onset of the feedback. According to the grand averages, this feature has the highest magnitude on the frontal cortex, as it is also presented in [50]. In the presented ERPs we observed the beginning of the event before the onset of the feedback, which can only be attributed to the readiness potential (RP) [51], which is a measure of the activity in the motor cortex of the brain leading up to voluntary muscle movement, and later due to the muscle movement itself.

From the behavior results we concluded that feedback is a salient factor influencing cognitive performance. We split the dataset into 4 groups, according to the feedback on the previous trials and the feedback on the current trial. The results showed that regardless of the previously given feedback, the feedback on the current trial determines changes in the signal. The fact that these two groups (1^{st} and 3^{rd} or 2^{nd} and 4^{th}) present similar behavior is due to the presence of the same cognitive process underlying a correct answer, or an incorrect one.

At the onset of the question, the stimulus, the question itself and the four possible answers are perceived in the same manner, regardless of the potential answer, because in the first 500 ms after the stimulus onset there are still sensory processes going on. After the onset of the feedback, the categorization of trials in correctly and incorrectly answered becomes clearly visible. The trials during association in which participants received “Good job!” as a feedback (either, true or positively biased) presented similar features with the trials that received “Incorrect answer” as a feedback. We believe that this behavior might be attributed to guessing, the participants being surprised by the feedback.

4.4 Conclusion and future considerations

The performance of the participants was not strongly influenced by the light intervention. According to the questionnaire results their perceived competence was influenced by positive reinforcement, which led to a higher performance during that phase. The absence of the encouraging feedback during the next phase led to a decrease in performance and perceived competence.

Regardless of the illumination setting or condition, the feedback seemed to be the most important factor when analyzing the performance scores.

The neural results present differences between correctly and incorrectly answered trials in the first second from the onset of the question, which represents a surprisingly upper limit to the duration of perceptual processes and the beginning of the subject’s decision.

The order of the phases had a great impact on performance levels. We observed that regardless of the illumination setting, after association, when the positively biased feedback was introduced, the performance dropped immediately, during the third phase. The order of the congruent phase before or after incongruent, had an impact on performance. For a future design, we consider that having a within subject design, including two conditions, congruent and incongruent, it is not a good solution, unless the population is large.

When we were replicating the results of the previous experiment, for a fair comparison, we consider that it would be we more convenient to have the same questions over each phase, for all the participants.

In order to have a better understanding of the arousal state we believe that as a complementary measurement to the questionnaire, we could introduce skin conductance and heart rate measurements. These would bring better insights about the participant's psychological and physiological state of arousal while performing the task.

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References

1. Koopman, P., Hoffman, R.R. “Work-arounds, make-work, and kludges”. *IEEE Transaction on Intelligent Systems*, 18, 6, 70-75, 2003.

2. Matthews R., McDonald N. J., Trejo L. J.(2005). Sensor Techniques: An Overview. Proceedings of the 2005 HCI International Conference, Las Vegas, Volume 11 - *Foundations of Augmented Cognition Psycho-Physiological,* CD-ROM. ISBN 0-8058-5807-5.

3. http://www.polytechpress.com/the-augcog-era-is-now/

4. Sheppard Jr., Joseph J., “Human color perception, A critical study of the Experimental Foundation”, *American Elsevier Publishing Company*, 1968, New York

5. J. Presko “Bright light therapy”. *Neuroendocrinol Lett* 29 (Suppl 1): 33-64, 2008

6. D. M. Warthen, B. J. Wiltgen and I. Provencion, “Light enhances learned fear”, *Proceedings of The National Academy of Sciences*, August 16, 2011, vol.108, no.33.

7. G.Vandewalle, C. Schmidt, G. Albouy, V.Sterpenich, A. Darsaud, G.Rauchs, P.Y. Berken, E. Balteau, C. Degueldre, A. Luxen, P. Maquet, D. J. Dijk , “Brain responses to violet, blue, and green monochromatic light exposures in humans: Proeminent role of blue light and the brainstem”, November 2007

8. F. Mahnke, “Color, environment, human response*”. New York: Van Nostrand Reinhold*, 1996

9. D. Warthen et al. (2011) “Light enhances learned fear”. *PNAS 13788-13793*, vol. 108, no.33

10. *Environmental Health Perspectives,* “What’s in a color?”, Volume 118, number 1, January 2010

11. *Valberg, Arne, Light Vision Color, Wiley, 2005*

12. D. K.Ballast, “Interior design reference manual”. Belmont, *CA: Professional Pub*, 2002

13. P. Davey, “True colors: The glorious polychrome of the past suggests a strong historical need for color, despite current reductive fashions.” *The Architectural Review* 204: 34-36, 1998

14. Linton, H., “Color consulting: A Survey of international color design.” *New York: Van Nostrand Reinhold*, 1991

15. Birren, F., “Color psychology and color therapy: A factual study of the influence of color on human life”. *New York: Citadel Press.* , 1989

16. M. C. Belcher, R. Kluczny, “A model for possible effects of light on decision making*”, Lighting Design and Application*, 1987, 2, 19 – 23

17. R. A. Baron, M. S. Rea, “Lighting to soothe the mood”, *Lighting for Design and Application*, 1991, 12, 30 – 32

18. I.Knez, “Effects of color of light on nonvisual psychological processes”, *Journal of Environmental Psychology,* 2001, 201-208

19. W. R. Daggett, J. E. Cobble and S. J. Gertel, “Color in an optimum learning environment”, *International Center for Leadership in Education*, March 2008

20. Schacter, Daniel L. (1992). “Priming and multiple memory systems: Perceptual mechanisms of implicit memory”. *Journal of Cognitive Neuroscience 4*(3): 244-256.

21. N. Kwallek, C. M. Lewis, *Appl. Ergon.* 21, 275 (1990).

22. N. J. Stone*, J. Environ. Psychol*. 23, 63 (2003)

23. A. J. Elliot, M. A. Maier, A. C. Moller, R. Friedman, J. Meinhardt*, J. Exp. Psychol. Gen. 136*, 154 (2007).

24. S. Soldat, R. C. Sinclair, M. M. Mark, *Soc. Cogn.* 15, 55 (1997).

25. R. Mehta, R. Zhu, “Blue or Red? Exploring the Effect of Color on Cognitive Task Performances”, *Science, Vol.323,* 2009

26. Chu S.(2008) Olfactory Conditioning of Positive Performance in Humans. *Chem.Senses 33:65-71*

27. A.Dijksterhuis, A. van Knippenberg, “The relation between perception and behavior, or how to win a game of trivial pursuit”, *Journal of Personality and Social Psychology, 1998*, Vol. 74, No.4, 865 – 877

28. J.A. Bargh, M. Chen, L. Burrows, “Automaticity of social behavior: direct effects of trait construct and stereotype-activation on action”, *Journal of Personal and Social Psychology,* 1996; 71(2):230-44.

29. Irving Kirsch et al., “The role of cognition in classical and operant conditioning”, Wiley, *Journal of Clinical Psychology, Vol. 60(4),* 369–392 (2004)

30. L.L. Jacoby, “Perceptual Enhancement: Persistent Effects of an Experience.” *Journal of Experimental Psychology: Learning, Memory, and Cognition, 9 (1)*, 21-38, 1983

31. D. Smeesters, J. (Elke) Liu, “The effect of color (red versus blue) on assimilation versus contrast in prime-to-behavior effects”, *Journal of Experimental Social Psychology 47* (2011) 653 - 656

32. Friedman, R. S., & Förster, J. (2010), “Implicit affective cues and attentional tuning: An integrative review”. *Psychological Bulletin, 136*, 875−893.

33. Slepian M. L. et al (2010) „Shedding light on insight: Priming bright ideas” *Journal of Experimental Social Psychology 46 (2010)* 696–700

34. VanRullen R. & Thorpe S. J. (2001) The Time Course of Visual Processing: From Early Perception to Decision-Making *Journal of Cognitive Neuroscience 13:4, pp. 454–461*

35. R.L. Solso, O.H. Maclin, M. K. Maclin, ”Cognitive Psychology”, Eighth Edition, Pearson, 2008

36. R.C. Atkinson, R.J. Herrnstein, G.Lindzey, R. D. Luce, ”Stevens’ Handbook of Experimental Psychology”, Vol. 2: “Learning and Cogntion” , Second Edition, *Wiley-Interscienc*e, 1988

37. A.R.Wagner, “Priming in STM: An information-processing mechanism for self-generated or retrieval-generated depression in performance. In *T.J.Tighe & R. N. Leaton (Eds.*), Habituation:Perspectives from child development, animal behavior, and neurophysiology (pp.95-128). Hillsdale, NJ: Erlbaum

38. A. Bandura, “Perceived Self-Efficacy in Cognitive Development and Functioning”, *Educational Psychology*, 28(2), 117-148

39. http://flavor.monell.org/~jlundstrom/research%20neuroimaging.html

40. Kramer, A.F. (1991). Physiological metrics of mental workload: A review of recent progress. In D.L. Damos (Ed.), Multiple-Task Performance (pp. 279-328). *London: Taylor & Francis.*

41. Tang, A.C., McKinney, C.J., Sutherland, M.T., Parra, L., Gerson, H., & Sajda, P. (2003). Extraction of single-trial ERPs from frontal and visual cortex from video game play despite continuous free eye movement. *ISBET Conference, University of New Mexico.*

42. http://www.quicktrivia.com/

43. Biosemi. Available from: http://www.biosemi.com/

44. Psychology Software Tools Inc. Available from: http://www.pstnet.com/

45. Irving Kirsch et al., “The role of cognition in classical and operant conditioning”, *Wiley, Journal of Clinical Psychology,* Vol. 60(4), 369–392 (2004)

46. K.H. Ting, P.C.W. Fung, C.Q. Chang, F.H.Y. Chan. Quantitative multichannel EEG measure predicting the optimal weaning from ventilator in ICU patients with acute respiratory failure. Journal *Medical Engineering & Physics,* Volume 28, Issue 8 , Pages 780-794, October 2006

47. http://www.cmb.ucdavis.edu/labs/luck-lab/working-memory-stimuli

48. A.I.Sburlea, T.Tsoneva, G.Garcia-Molina, ”Increasing cognitive ability with light conditioning”, Philips Technical Note

49. http://flavor.monell.org/~jlundstrom/research%20neuroimaging.html

50. N. Yeung, C.B. Holroyd, J.D. Cohen, ERP Correlates of Feedback and Reward Processing in the Presence and Absence of Response Choice, Cerebral Cortex May 2005; 15:535-544

51. H. Masaki, N. Wild-WalI, J. Sangals, W, Sommer, The functional locus of the lateralized readiness potential, Psychophysiology, 41 (2004), 220–230.

Appendix A

Intrinsic Motivation Inventory questionnaire

For each of the following statements, please indicate how true it is for you, using the following scale:

1	2	3	4	5	6	7
not at all true			somewhat true			very true

Perceived Competence

1) I think I am pretty good at this activity.

   1 2 3 4 5 6 7

2) I think I did pretty well at this activity, compared to other students.

   1 2 3 4 5 6 7

3) After working at this activity for awhile, I felt pretty competent.

   1 2 3 4 5 6 7

4) I am satisfied with my performance at this task.

   1 2 3 4 5 6 7

5) I was pretty skilled at this activity.

   1 2 3 4 5 6 7

6) This was an activity that I couldn’t do very well. (R)

   1 2 3 4 5 6 7

Effort/Importance

7) I put a lot of effort into this.

1 2 3 4 5 6 7

8) I didn’t try very hard to do well at this activity. (R)

1 2 3 4 5 6 7

9) I tried very hard on this activity.

1 2 3 4 5 6 7

10) It was important to me to do well at this task.

1 2 3 4 5 6 7

11) I didn’t put much energy into this. (R)

1 2 3 4 5 6 7

Appendix B

Reaction time for correctly and incorrectly answered trials during the first day (Figure B.1) and during the second day (Figure B.2).

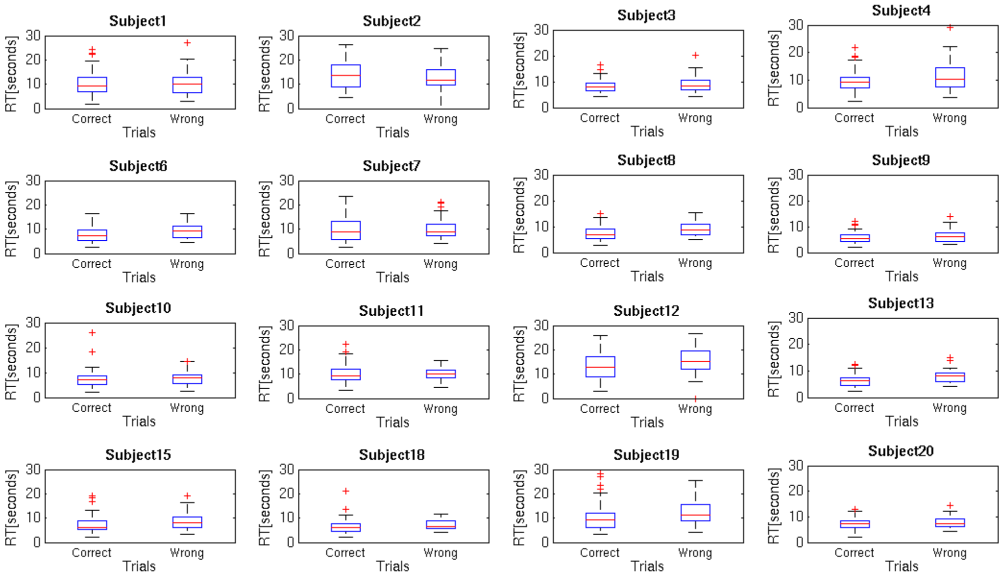


Figure B.1. Reaction time for correct/ wrong answered trials for each participant during the first day of the experiment

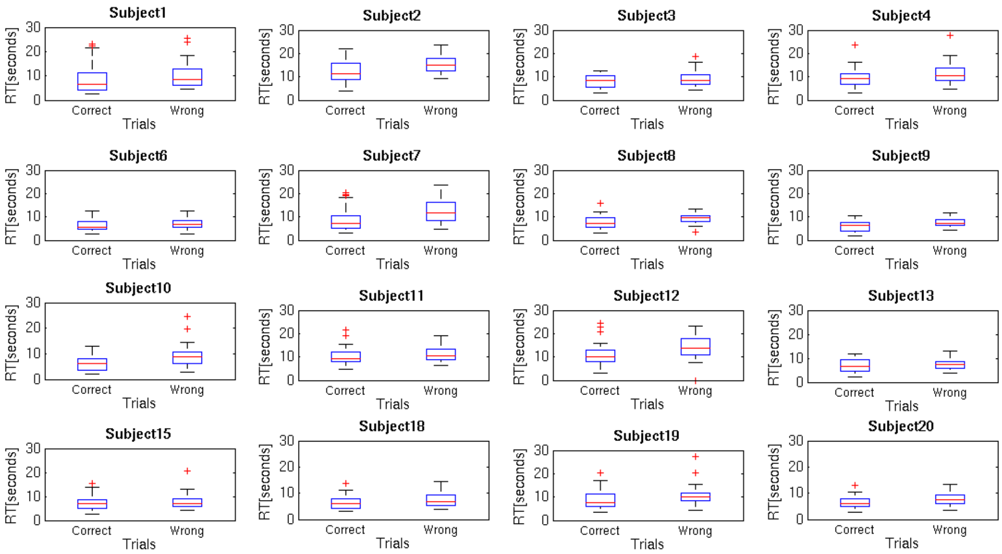


Figure B.2. Reaction time for correct/ wrong answered trials for each participant during the second day of the experiment

Appendix C1

Single trial ERP

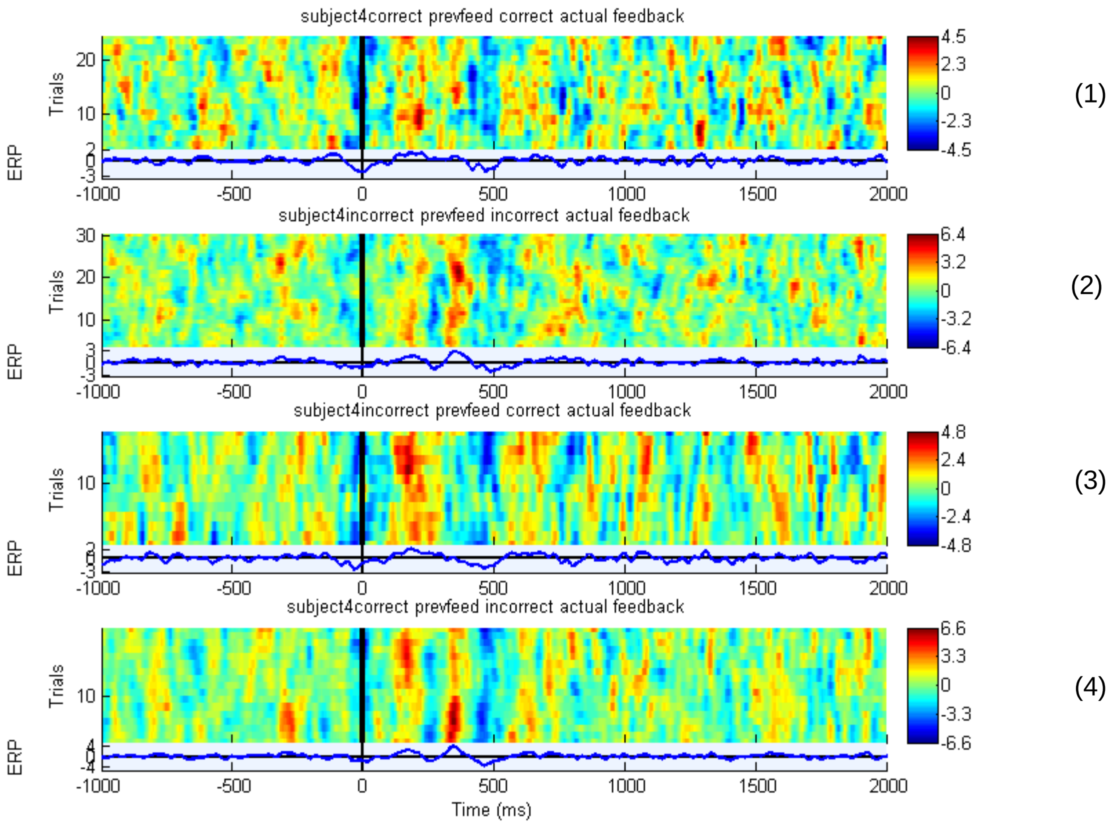
Figure C1.1 presents chronologically ordered trials split in four groups according to the feedback on the previous question and the feedback on the current question.

This categorization led to the following groups:

1. correct previous feedback – correct current feedback
2. incorrect previous feedback – incorrect current feedback
3. incorrect previous feedback – correct current feedback
4. correct previous feedback – incorrect current feedback

Figure C1.1 presents in both (a) and (b), corresponding to two typical participants, a similar feature around 350ms, for groups (1) and (3). The fact that these two groups present similar behavior is due to the presence of the same cognitive process underlying a correct answer, or an incorrect one. This feature is a positive peak, which is not detected in the other groups, (2) and (4). All the subplots present trials in chronological order. For an overview of all the participants, see Appendix C.

(a)



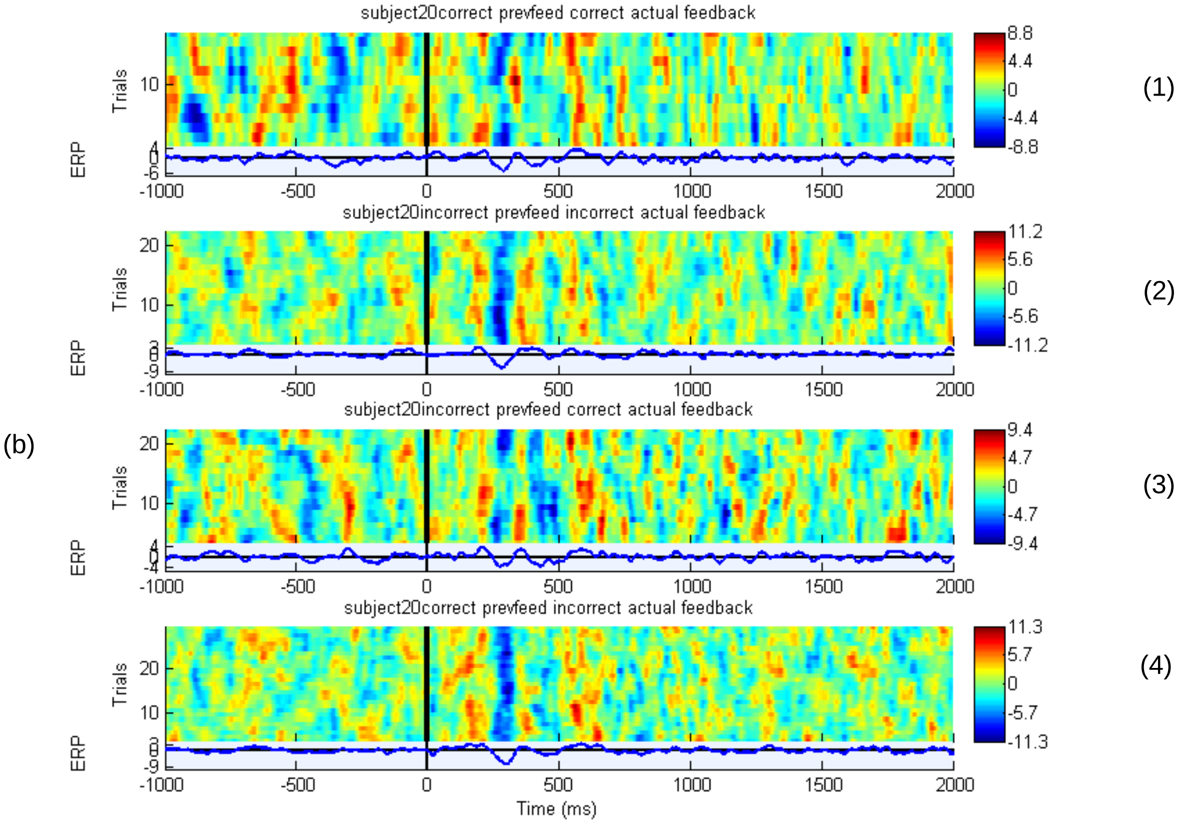
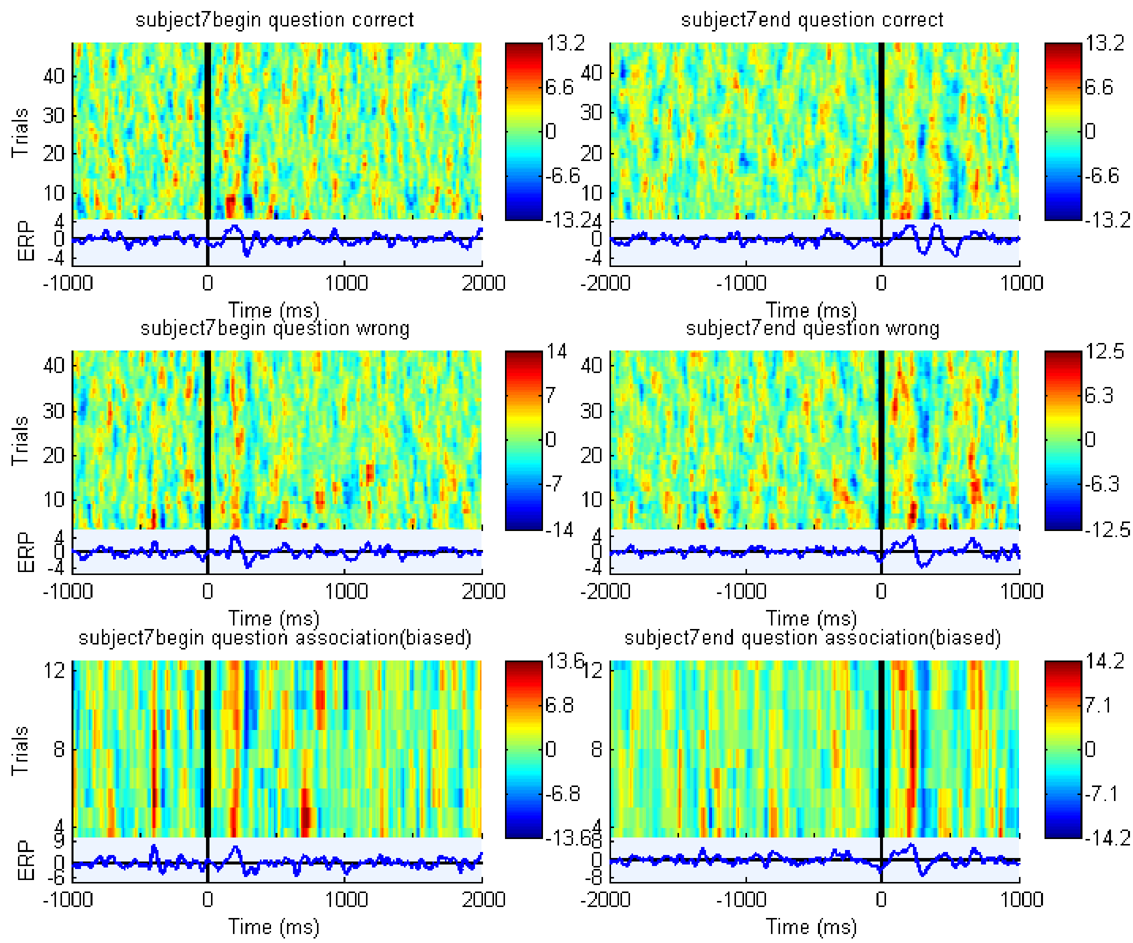


Figure C1.1. ERP images of trials chronological ordered grouped according to the previous feedback and the actual response (1. correct previous feedback, correct actual response; 2. incorrect previous feedback, incorrect actual response; 3. incorrect previous feedback, correct actual response; 4 correct previous feedback, incorrect actual response)

Figure C1.2 presents in chronological order, the trials with correct, wrong responses and the ones that received encouraging feedback, during association. The vertical black line represents the onset of the question (a), and the onset of the feedback (b). It can be seen that the ERP signal for the beginning of the question presents no significant difference when comparing the signal for the different types of feedback.

In the first 100 ms after the onset of the question there is a positive peak in all three cases. This result is expected because of the sensory processes at the beginning of the question (i.e. reading).

Regarding the onset of the feedback, the trials that received correct feedback presented a second positive peak, at 350 ms, while the trials that received incorrect feedback, not. The last subplot presents the trials that received encouraging feedback. The ERP for the trials during association that received correct feedback (biased and true) is very similar to the ERP of the incorrectly answered trials, but the number of trials in this category is very small to establish a significant difference.



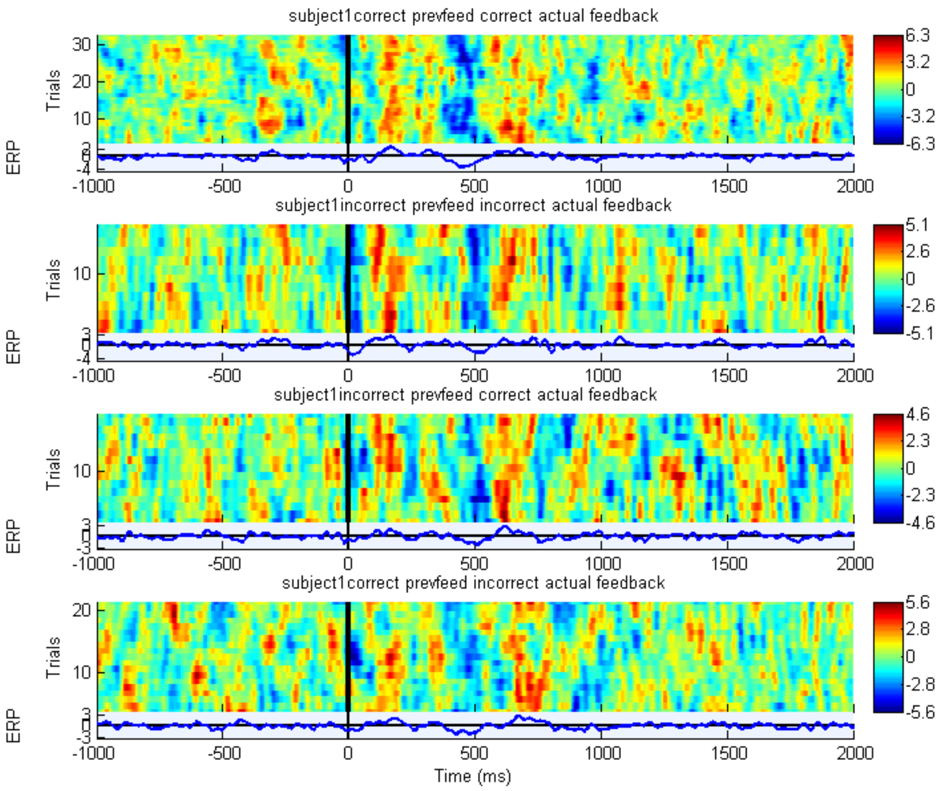
(a) *(b)*

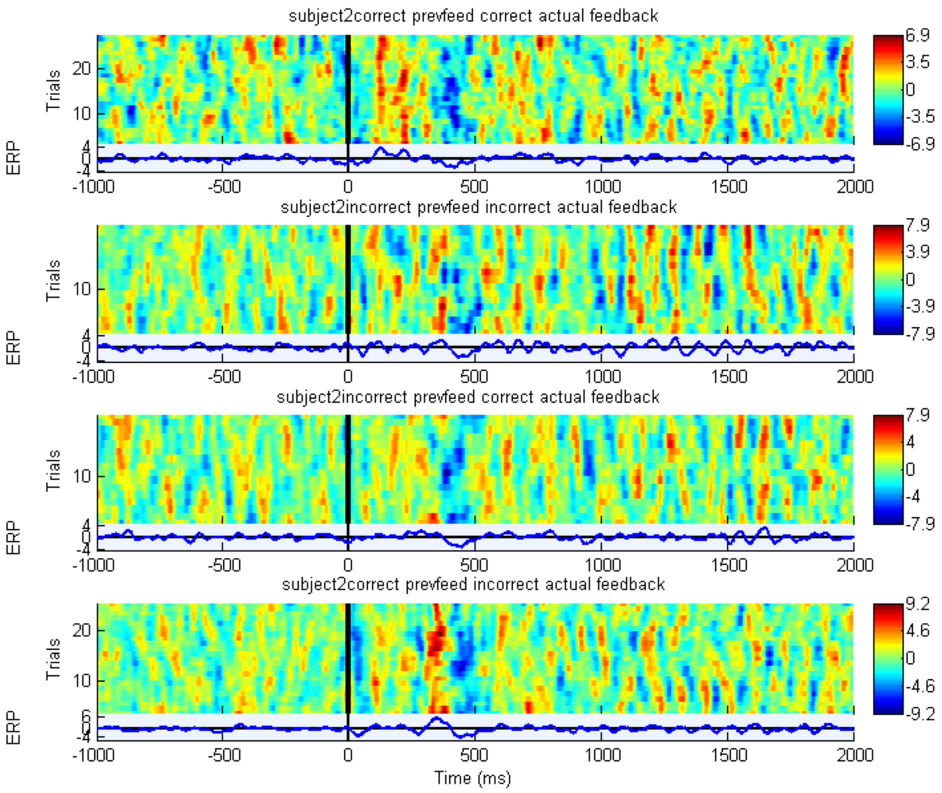
Figure C1.2. ERP images of time windows showing the onset of the question and the end of the question for correctly and wrongly answered trials.

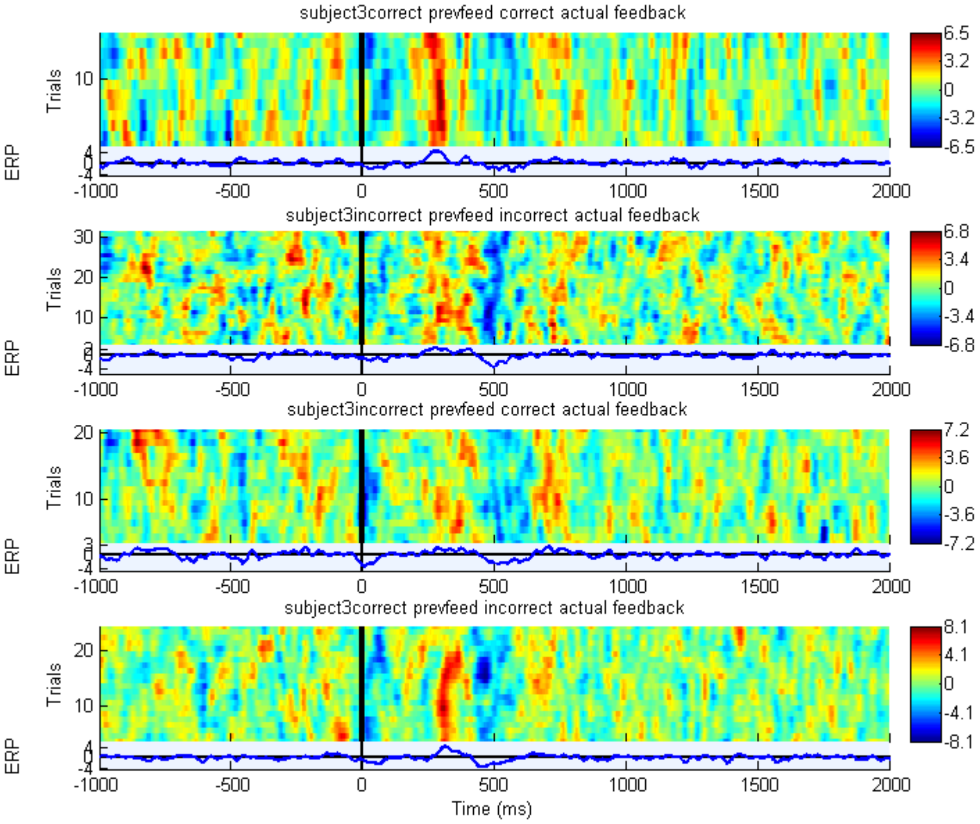
For an overview of all the participants, see Appendix C2 and C3.

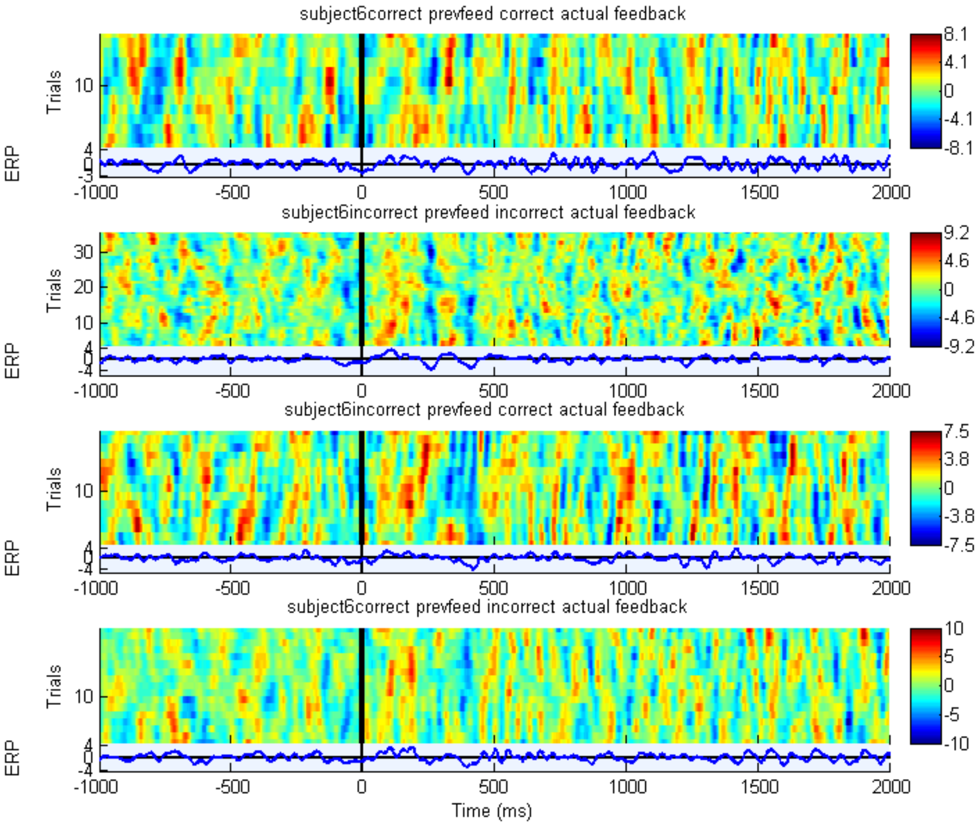
Appendix C2

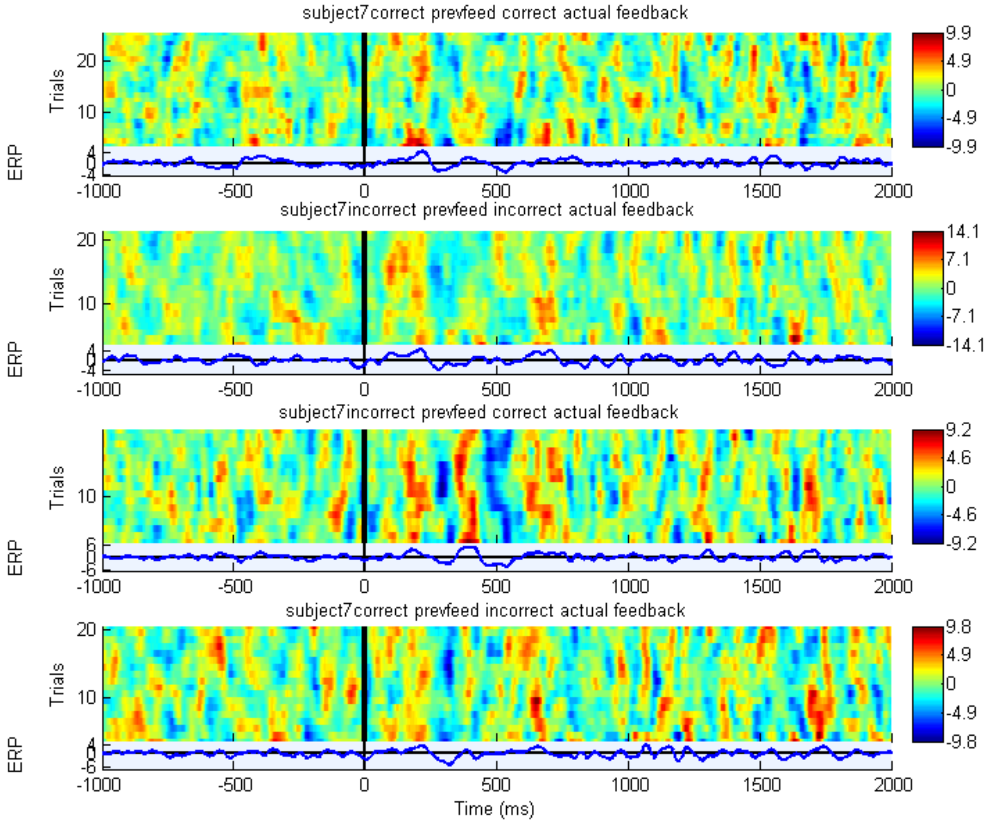
Categorization of previous feedback and the actual feedback

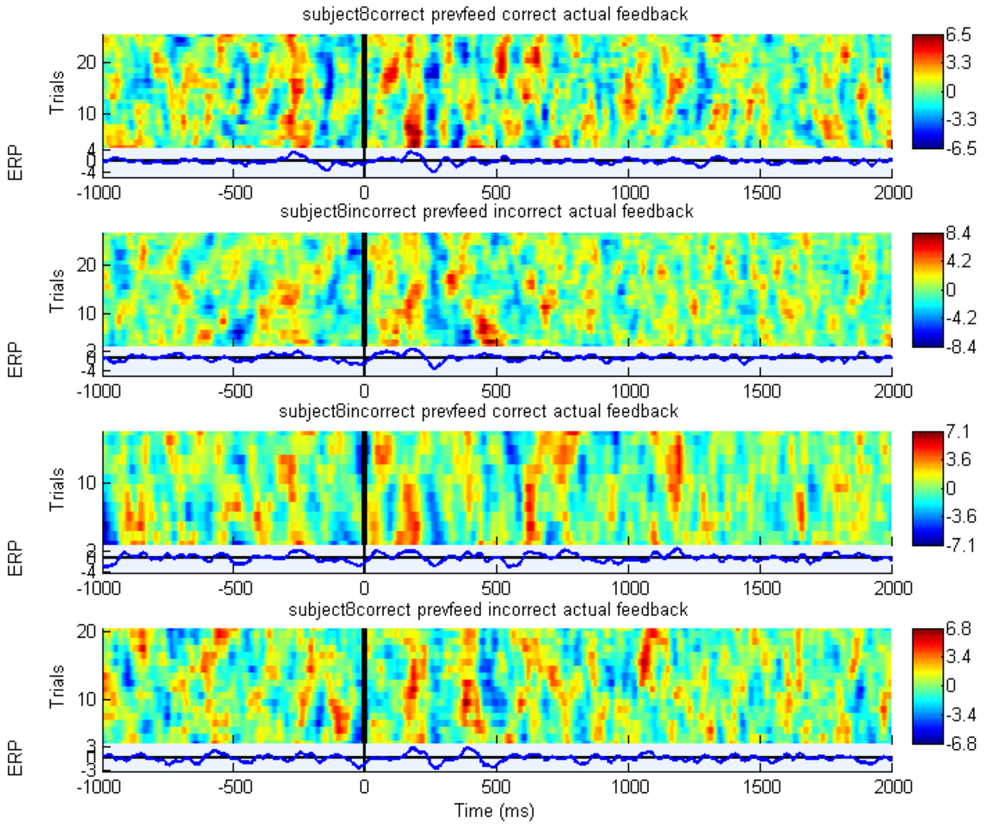


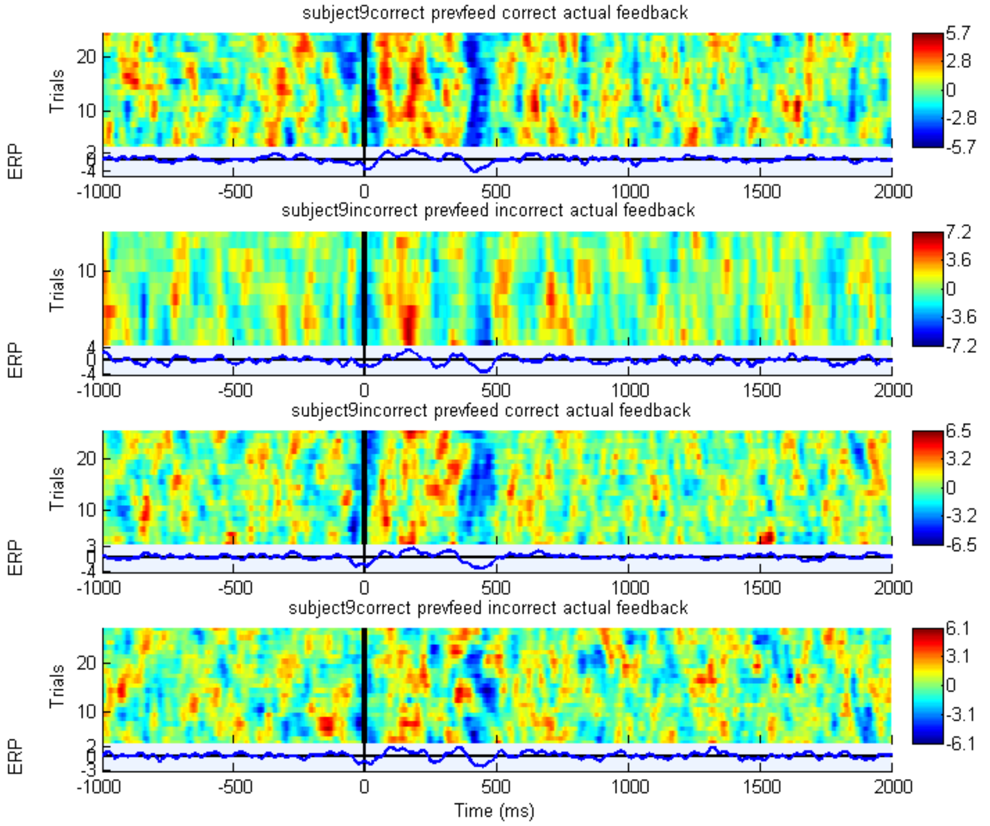


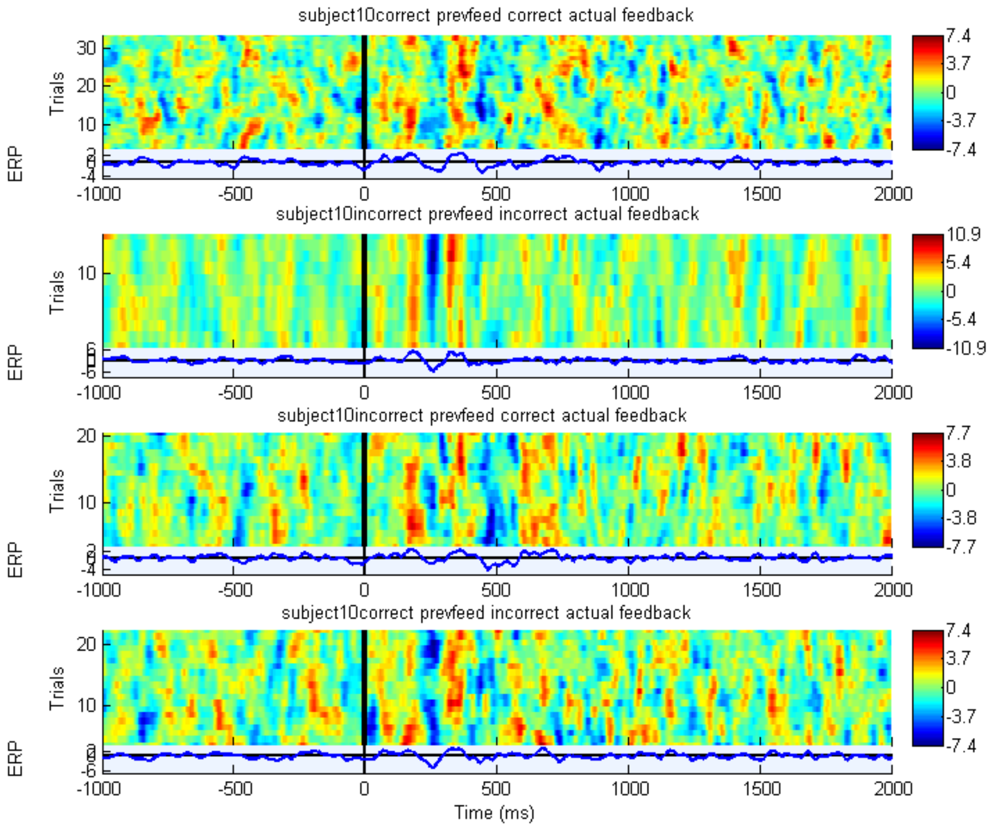

subject3correct prevfeed correct actual feedback
subject3incorrect prevfeed incorrect actual feedback
subject3incorrect prevfeed correct actual feedback
subject3correct prevfeed incorrect actual feedback
Trials
ERP
Time (ms)

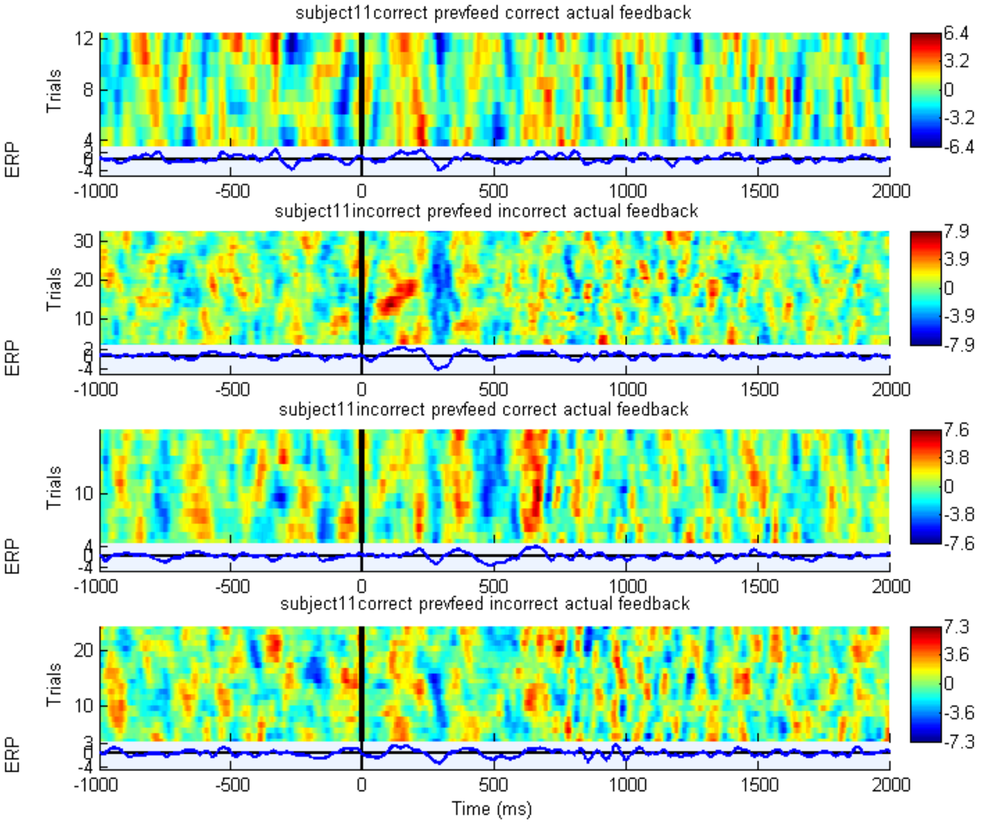

subject6correct prevfeed correct actual feedback
subject6incorrect prevfeed incorrect actual feedback
subject6incorrect prevfeed correct actual feedback
subject6correct prevfeed incorrect actual feedback
Trials
ERP
Time (ms)


subject7correct prevfeed correct actual feedback
subject7incorrect prevfeed incorrect actual feedback
subject7incorrect prevfeed correct actual feedback
subject7correct prevfeed incorrect actual feedback
Trials
ERP
Time (ms)


subject8correct prevfeed correct actual feedback
subject8incorrect prevfeed incorrect actual feedback
subject8incorrect prevfeed correct actual feedback
subject8correct prevfeed incorrect actual feedback
Trials
ERP
Time (ms)


subject9correct prevfeed correct actual feedback
subject9incorrect prevfeed incorrect actual feedback
subject9incorrect prevfeed correct actual feedback
subject9correct prevfeed incorrect actual feedback
Trials
ERP
Time (ms)
-1000
-500
0
500
1000
1500
2000
5.7
2.8
-2.8
-5.7
7.2
3.6
-3.6
-7.2
6.5
3.2
-3.2
-6.5
6.1
3.1
-3.1
-6.1


subject10correct prevfeed correct actual feedback
subject10incorrect prevfeed incorrect actual feedback
subject10incorrect prevfeed correct actual feedback
subject10correct prevfeed incorrect actual feedback
Trials
ERP
Time (ms)
-1000
-500
0
500
1000
1500
2000
7.4
3.7
-3.7
-7.4
10.9
5.4
-5.4
-10.9
7.7
3.8
-3.8
-7.7


subject11correct prevfeed correct actual feedback
6.4
3.2
0
-3.2
-6.4
subject11incorrect prevfeed incorrect actual feedback
7.9
3.9
0
-3.9
-7.9
subject11incorrect prevfeed correct actual feedback
7.6
3.8
0
-3.8
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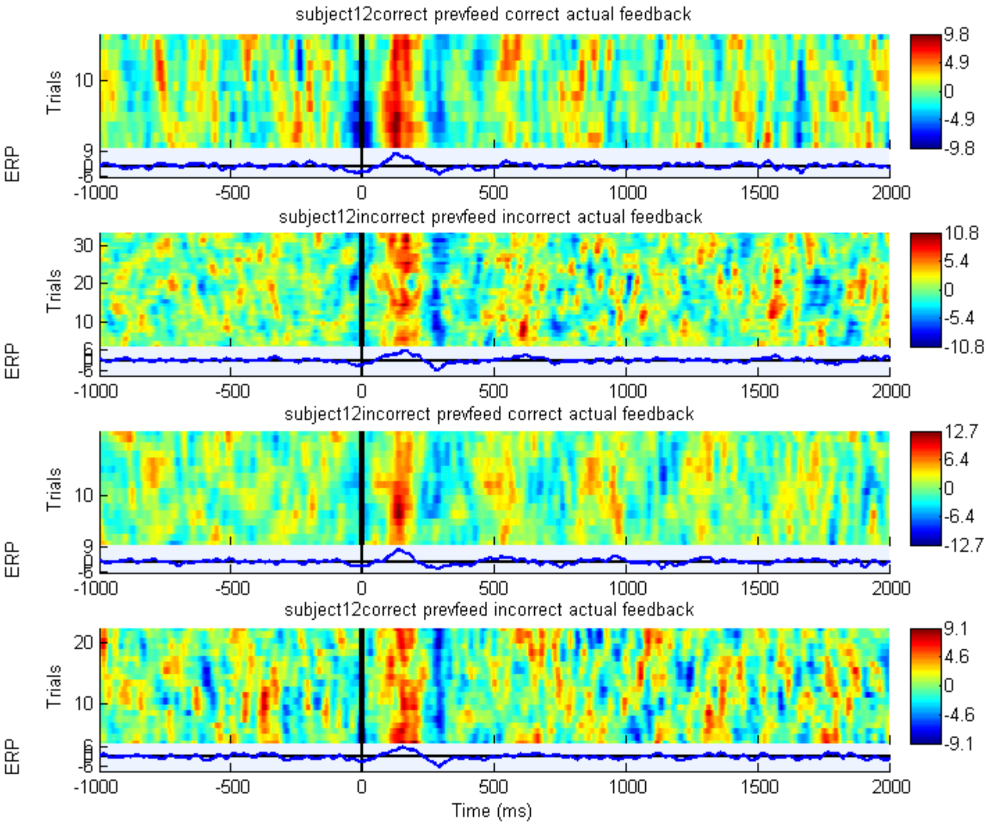
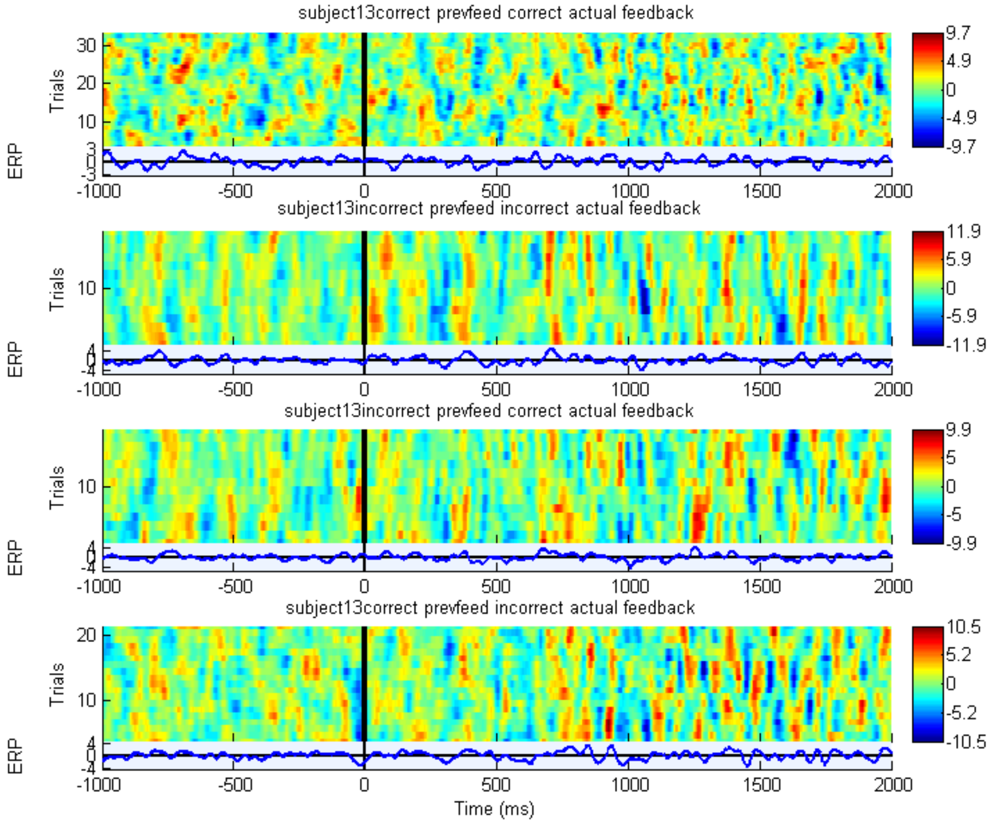
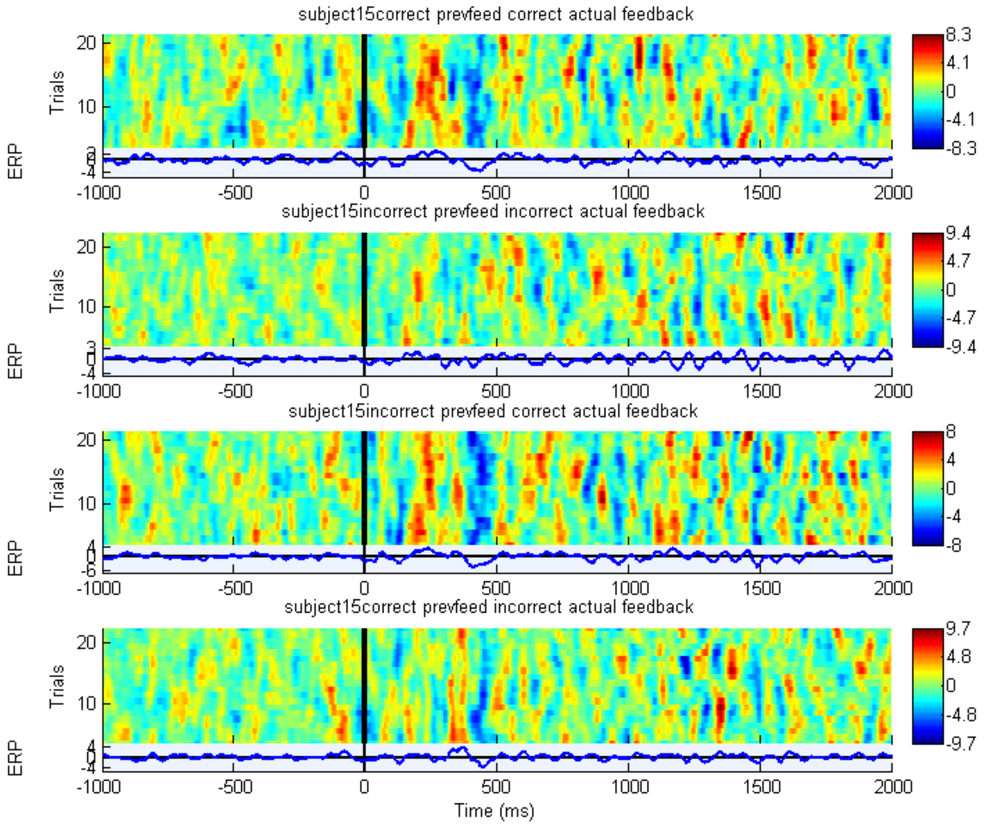
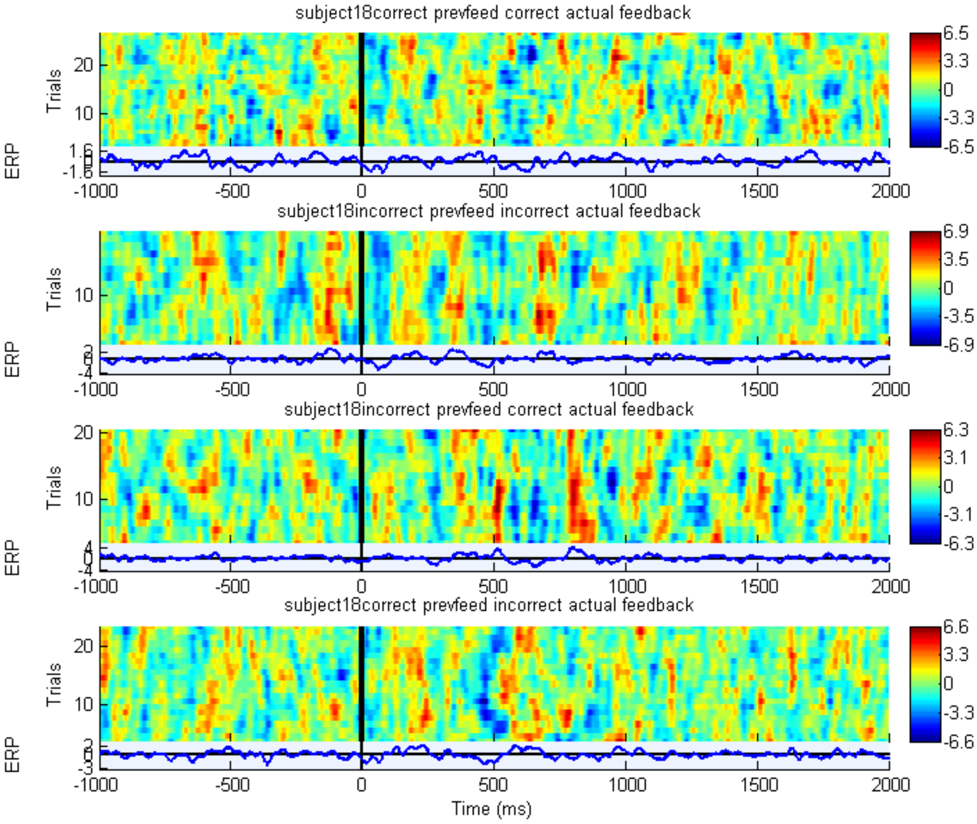
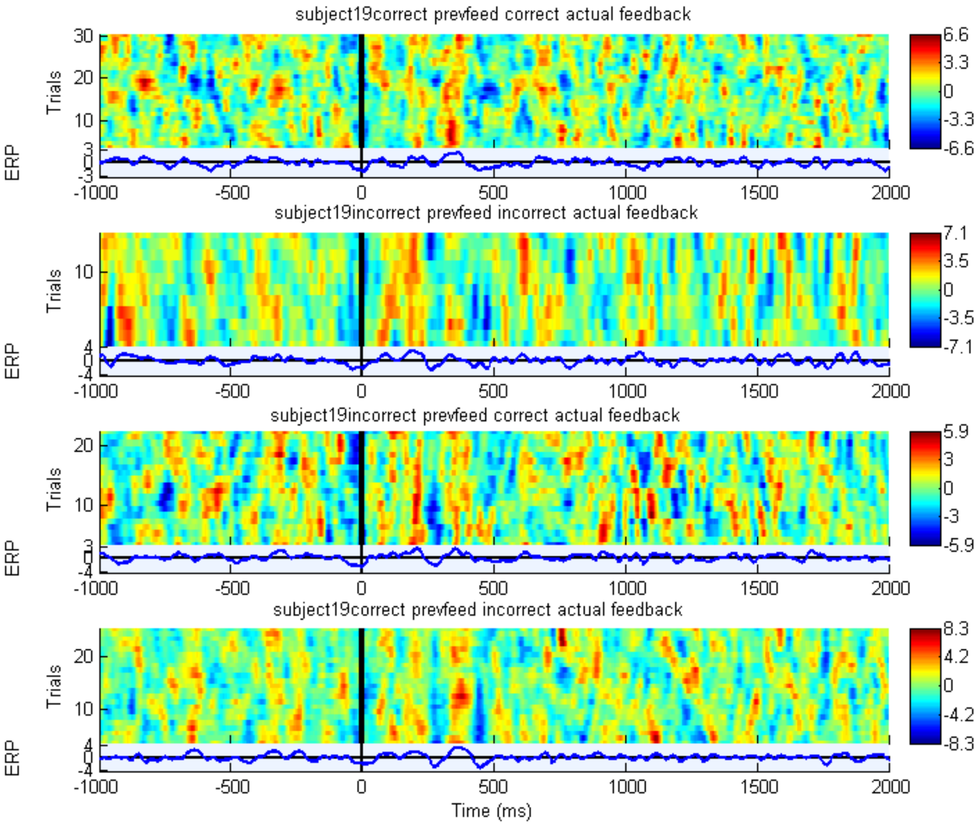
subject11correct prevfeed incorrect actual feedback
7.3
3.6
0
-3.6
-7.3
Trials
ERP
Time (ms)


subject12correct prevfeed correct actual feedback
9.8
4.9
0
-4.9
-9.8
subject12incorrect prevfeed incorrect actual feedback
10.8
5.4
0
-5.4
-10.8
subject12incorrect prevfeed correct actual feedback
12.7
6.4
0
-6.4
-12.7
subject12correct prevfeed incorrect actual feedback
9.1
4.6
0
-4.6
-9.1
Trials
ERP
Time (ms)


subject13correct prevfeed correct actual feedback
subject13incorrect prevfeed incorrect actual feedback
subject13incorrect prevfeed correct actual feedback
subject13correct prevfeed incorrect actual feedback
Trials
ERP
Time (ms)

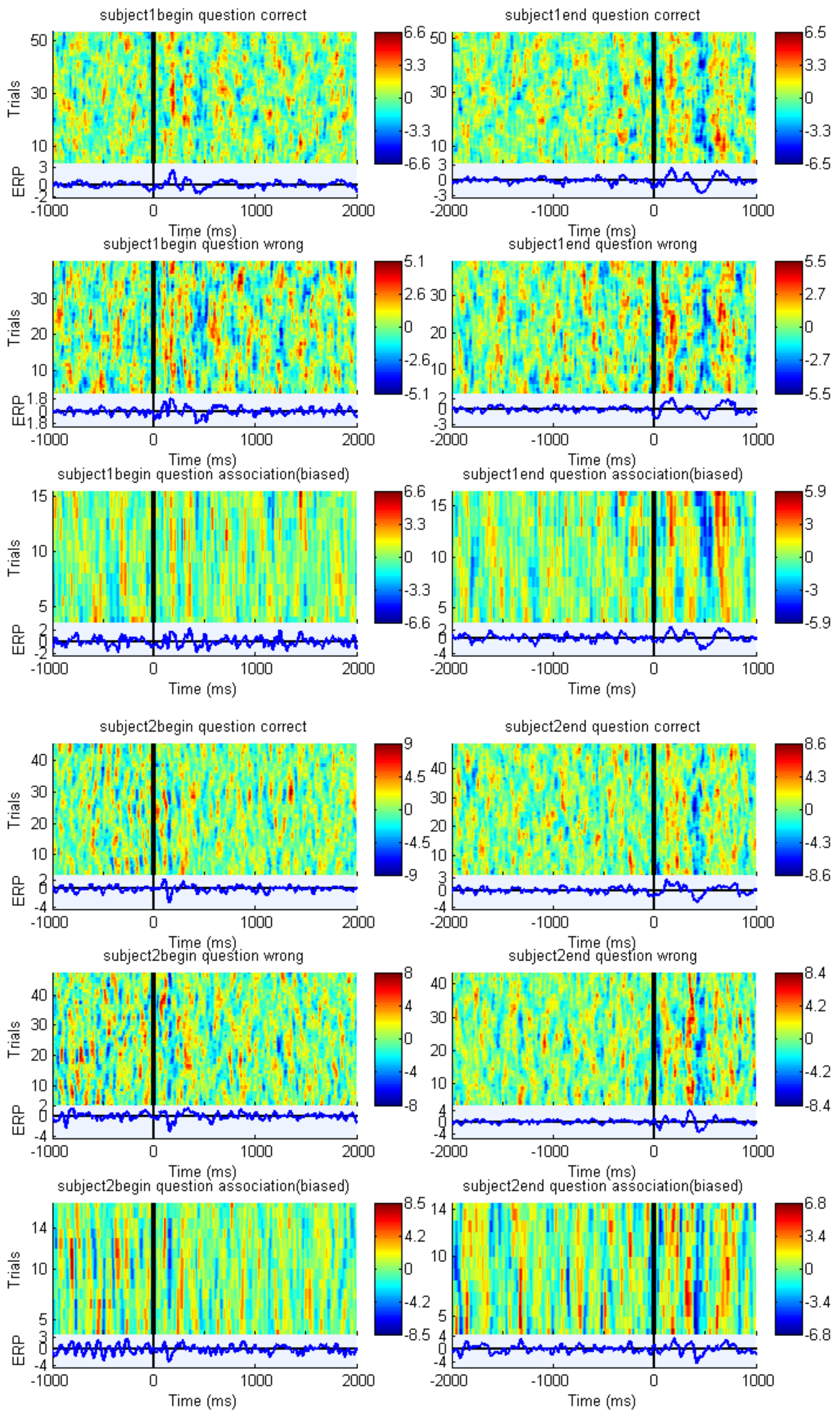

subject15correct prevfeed correct actual feedback
subject15incorrect prevfeed incorrect actual feedback
subject15incorrect prevfeed correct actual feedback
subject15correct prevfeed incorrect actual feedback
Trials
ERP
Time (ms)

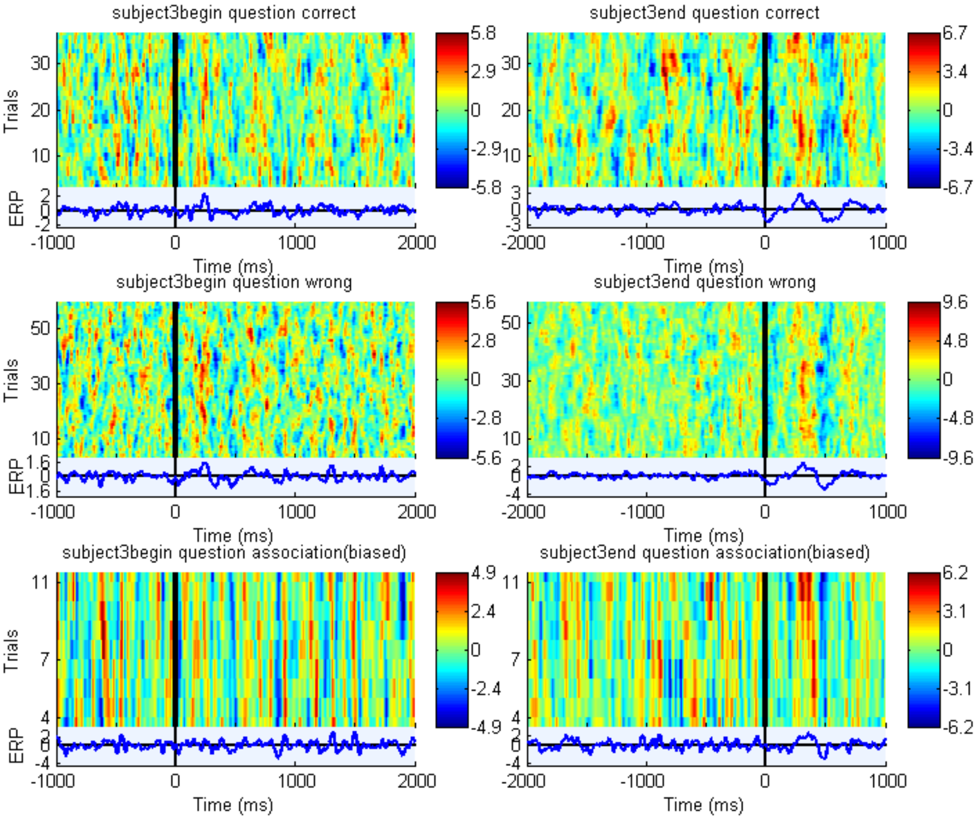

subject18correct prevfeed correct actual feedback
subject18incorrect prevfeed incorrect actual feedback
subject18incorrect prevfeed correct actual feedback
subject18correct prevfeed incorrect actual feedback
Trials
ERP
-1000
-500
0
500
1000
1500
2000
Time (ms)

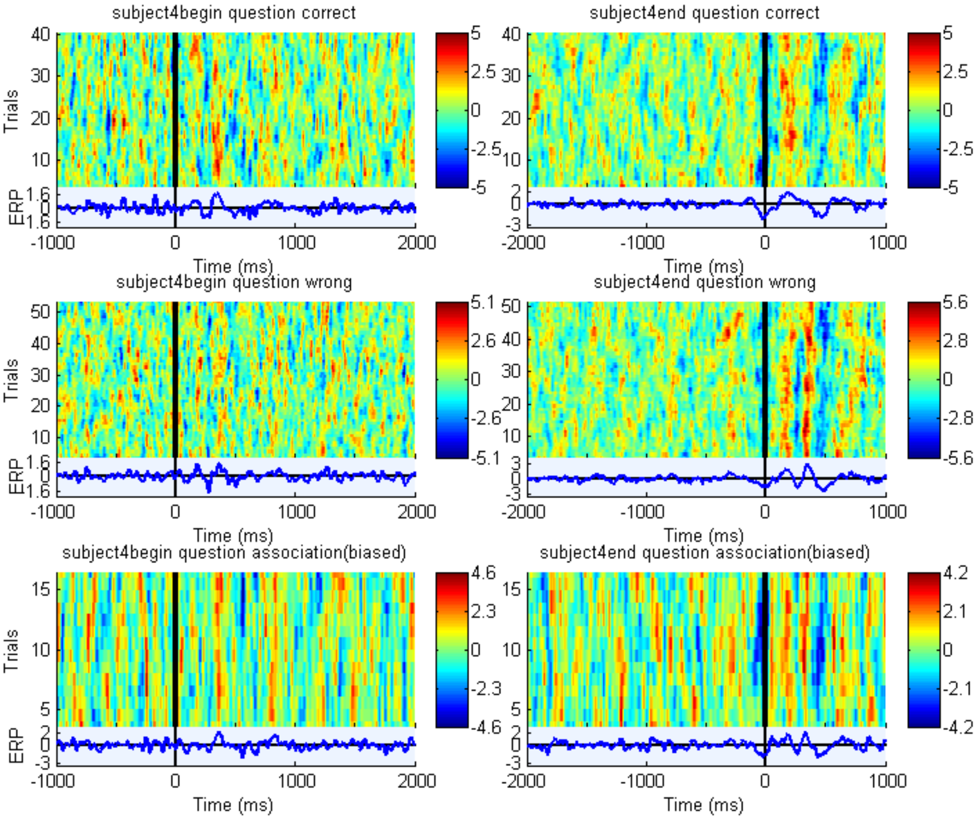

subject19correct prevfeed correct actual feedback
subject19incorrect prevfeed incorrect actual feedback
subject19incorrect prevfeed correct actual feedback
subject19correct prevfeed incorrect actual feedback
Trials
ERP
-1000
-500
0
500
1000
1500
2000
Time (ms)

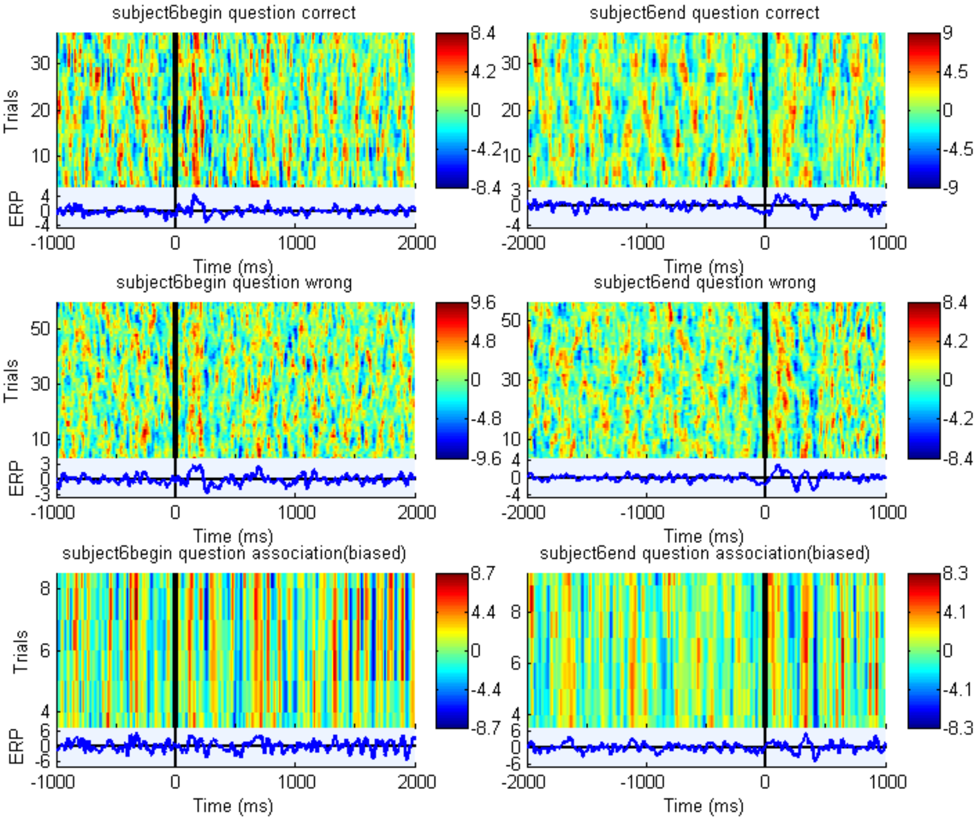
Appendix C3

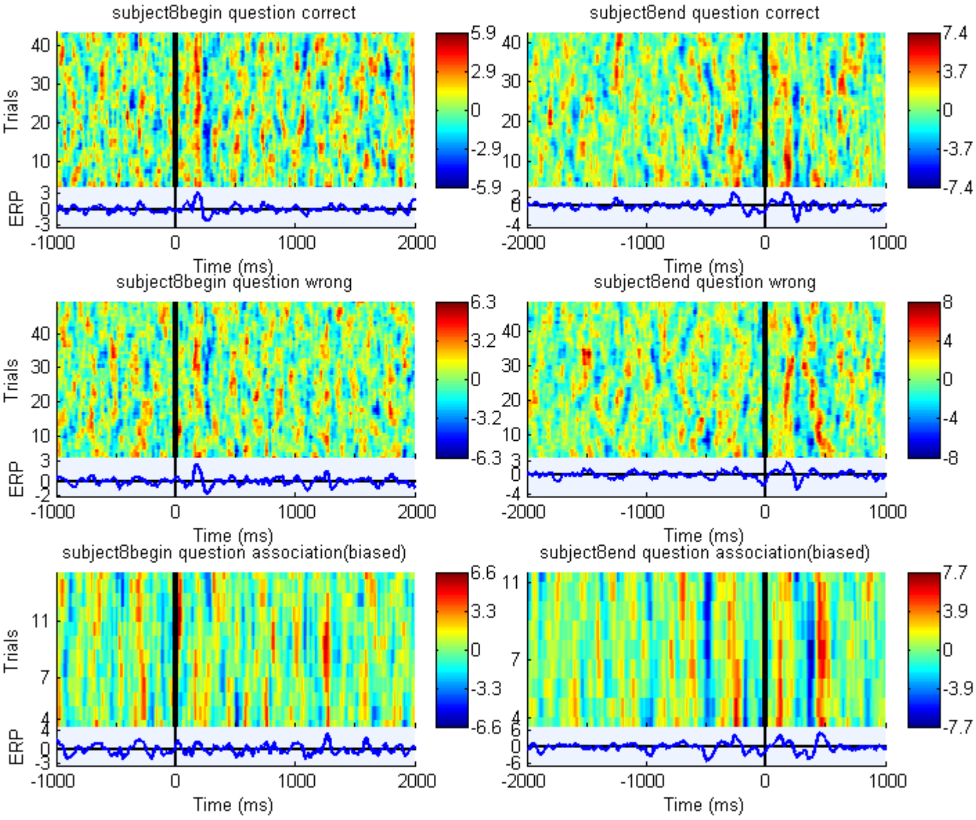
ERP images of time windows showing the onset of the question and the end of the question for correctly and wrongly answered trials.

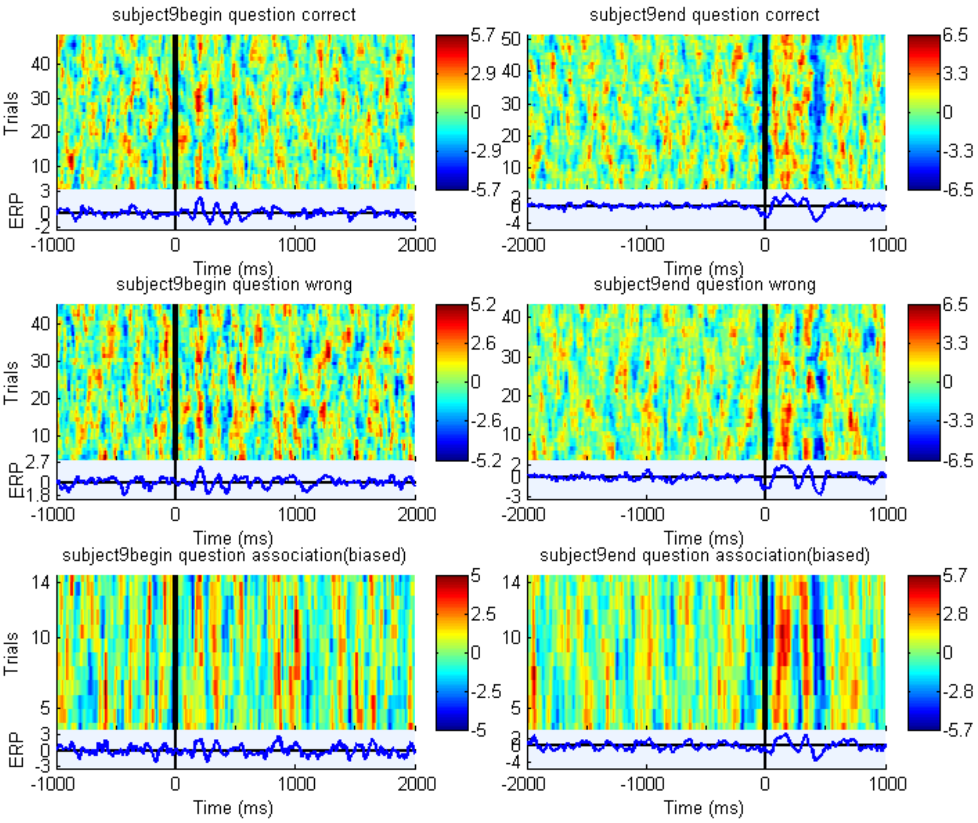


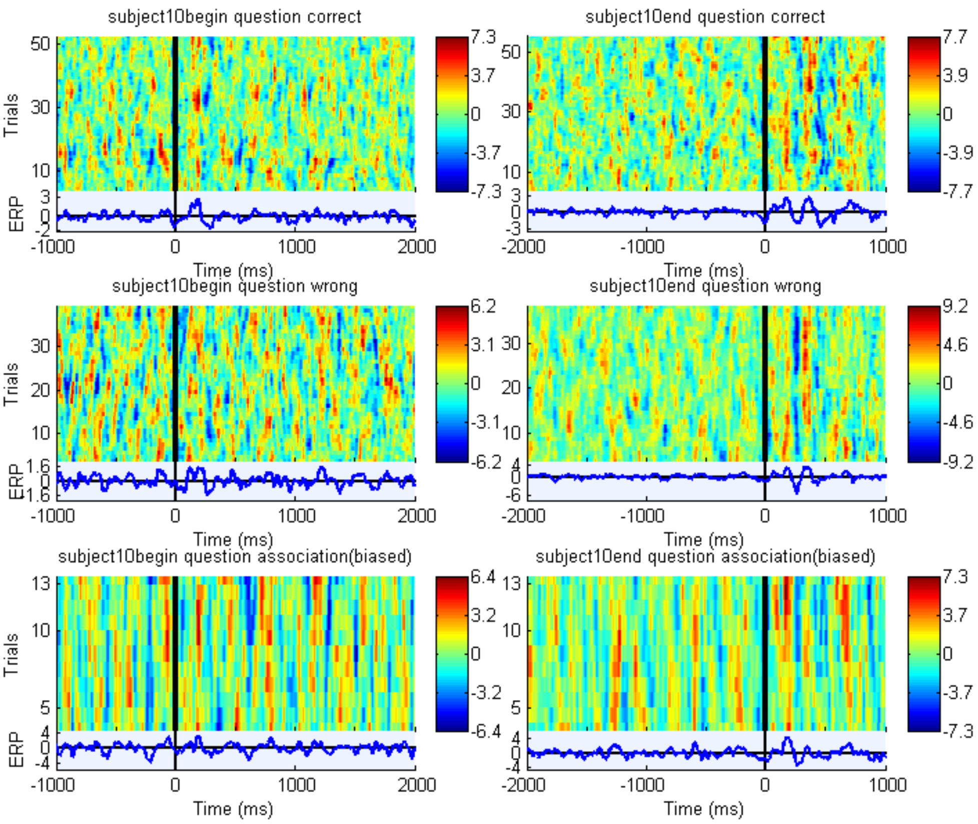

subject3begin question correct
subject3end question correct
subject3begin question wrong
subject3end question wrong
subject3begin question association(biased)
subject3end question association(biased)
Trials
ERP
Time (ms)

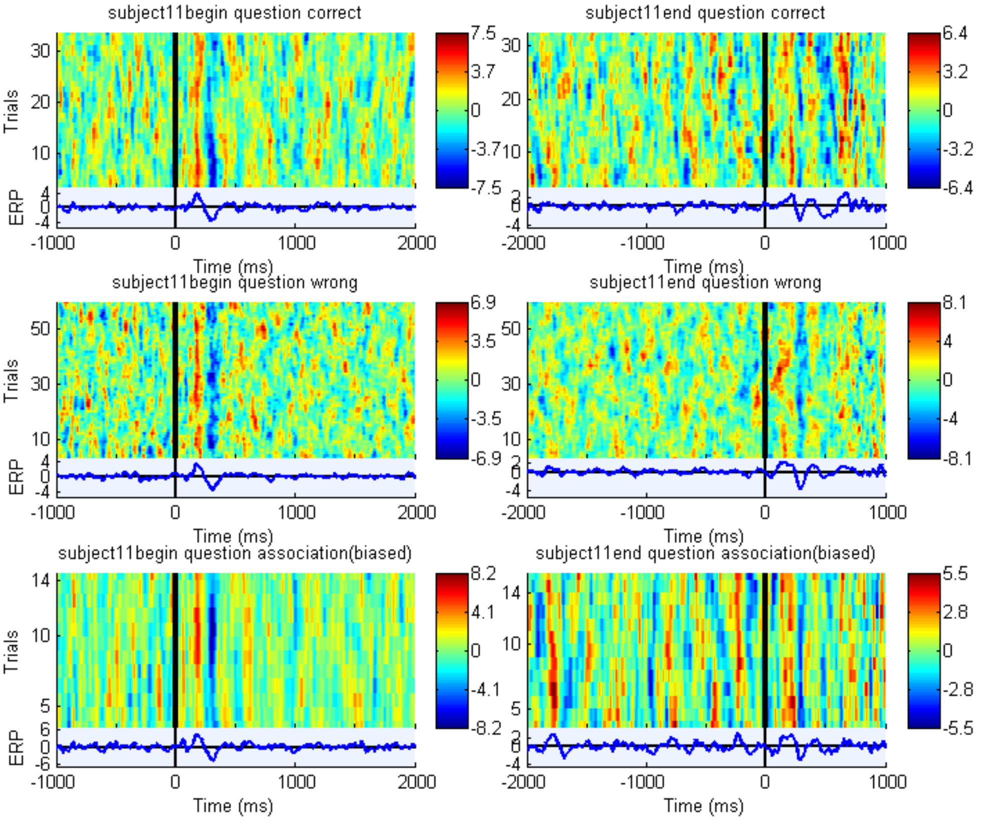

subject4begin question correct
subject4end question correct
subject4begin question wrong
subject4end question wrong
subject4begin question association(biased)
subject4end question association(biased)
Trials
ERP
Time (ms)

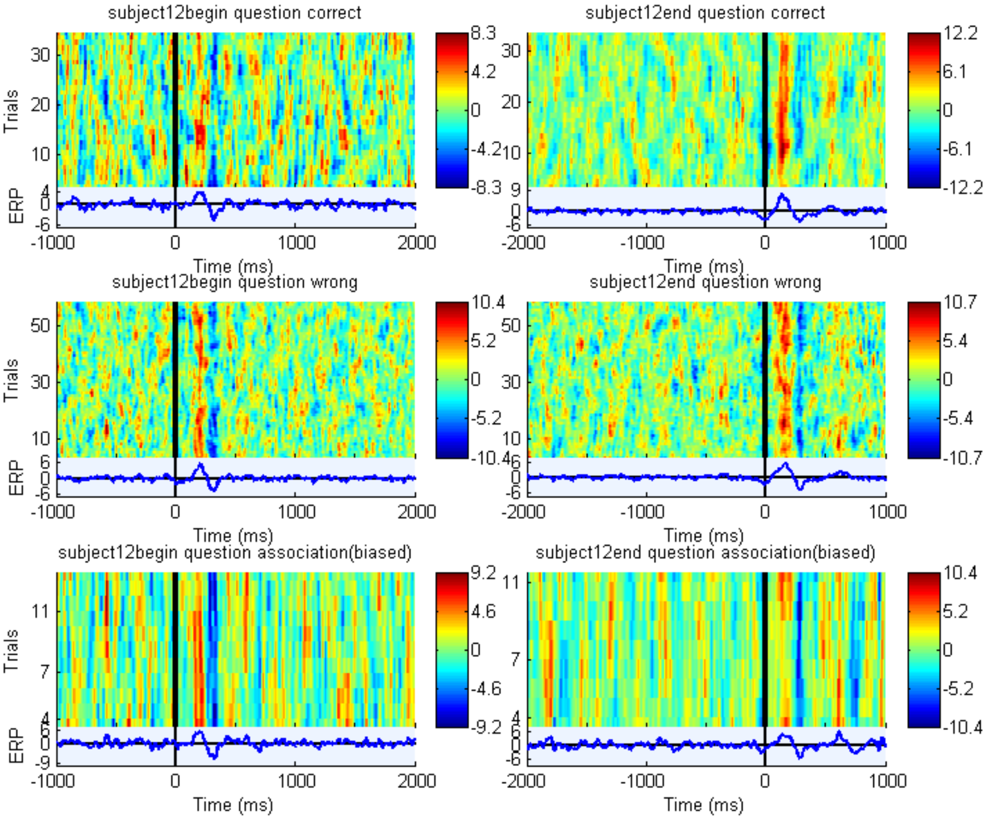

subject6begin question correct
subject6end question correct
subject6begin question wrong
subject6end question wrong
subject6begin question association(biased)
subject6end question association(biased)
Trials
ERP
Time (ms)

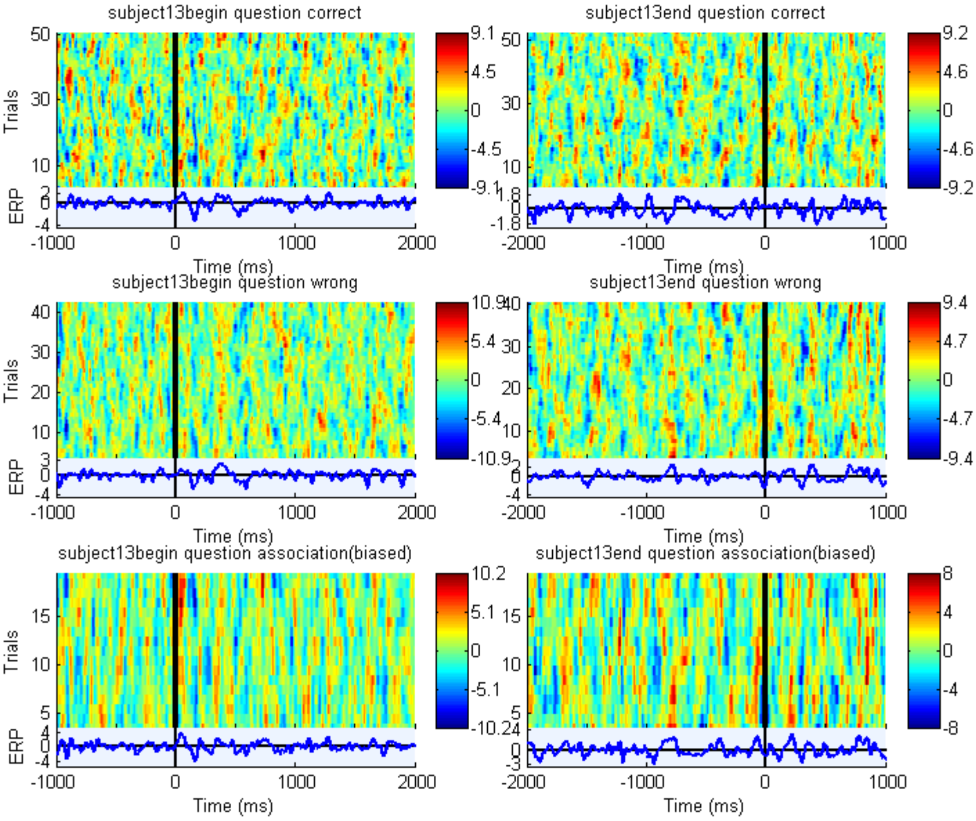

subject8begin question correct
subject8end question correct
subject8begin question wrong
subject8end question wrong
subject8begin question association(biased)
subject8end question association(biased)
Trials
ERP
Time (ms)

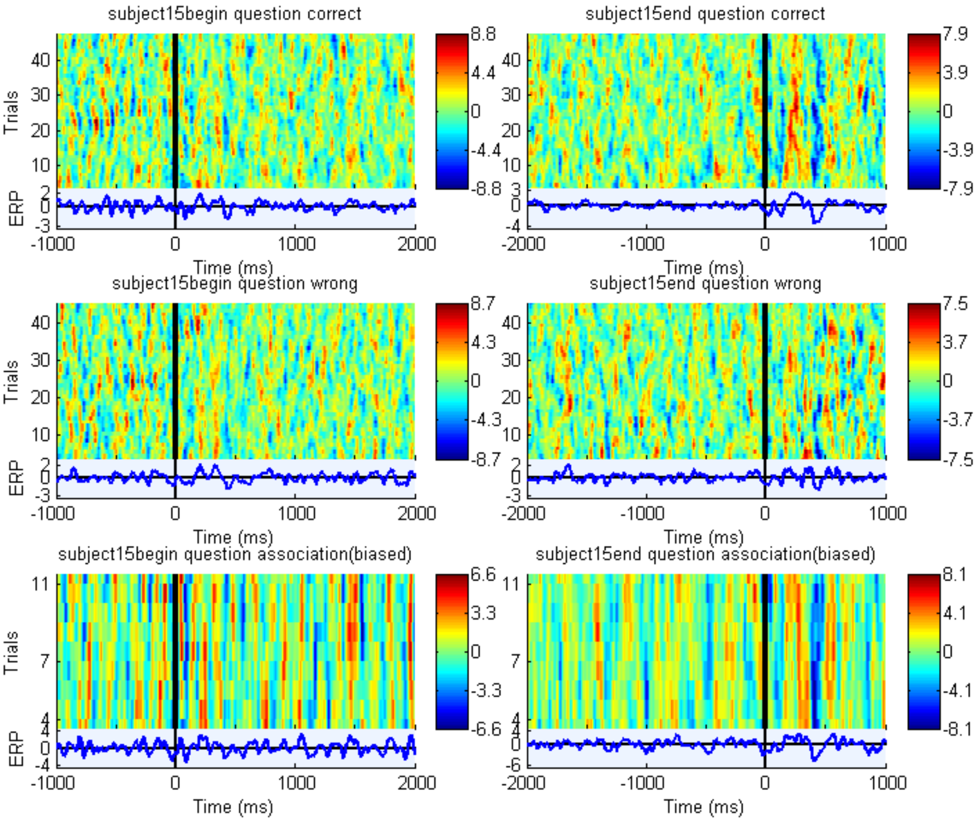

subject9begin question correct
subject9end question correct
subject9begin question wrong
subject9end question wrong
subject9begin question association(biased)
subject9end question association(biased)
Trials
ERP
Time (ms)

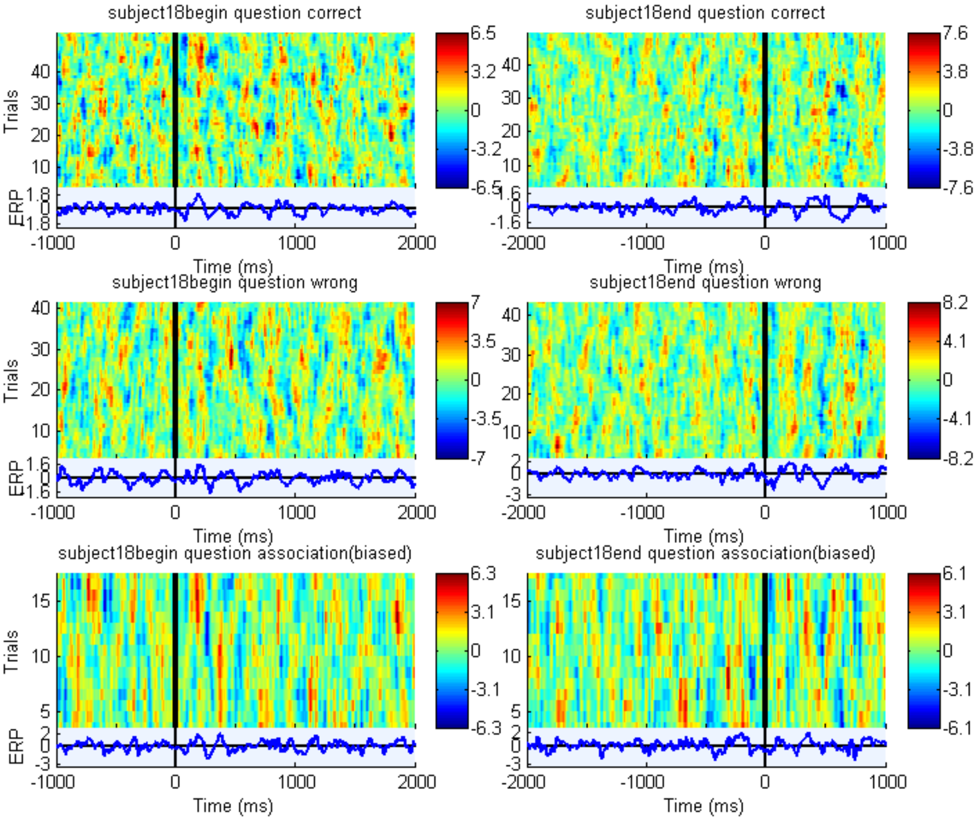

subject10begin question correct
subject10end question correct
subject10begin question wrong
subject10end question wrong
subject10begin question association(biased)
subject10end question association(biased)
Trials
ERP
Time (ms)

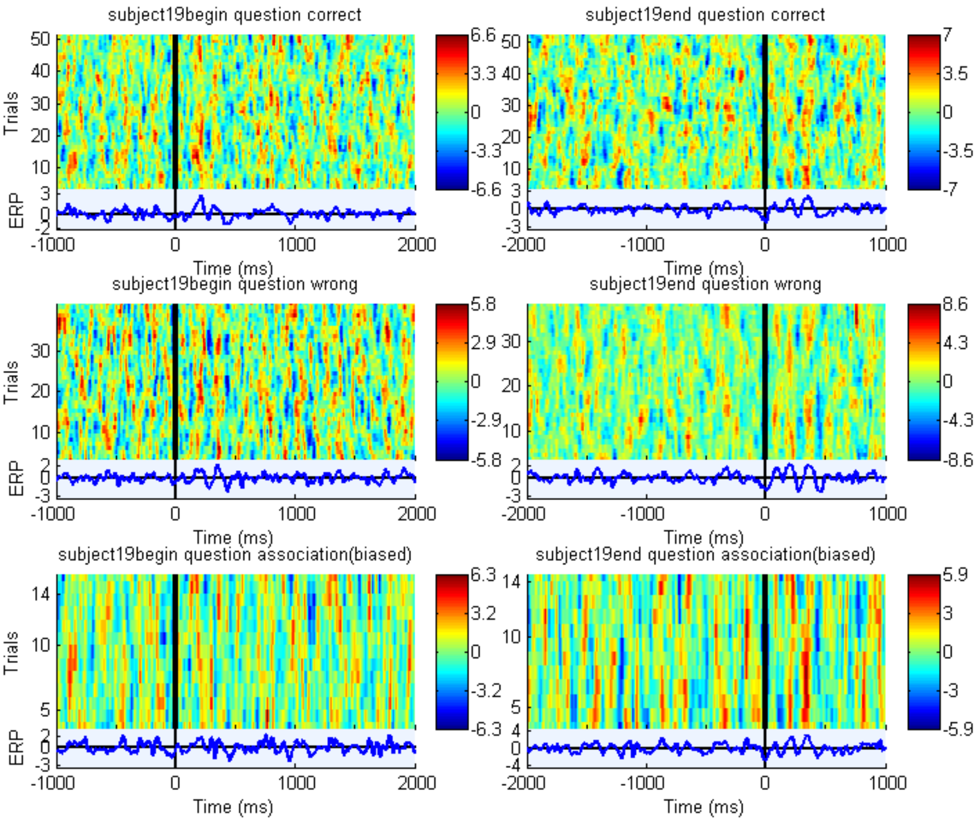

subject11begin question correct
subject11end question correct
subject11begin question wrong
subject11end question wrong
subject11begin question association(biased)
subject11end question association(biased)
Trials
ERP
Time (ms)

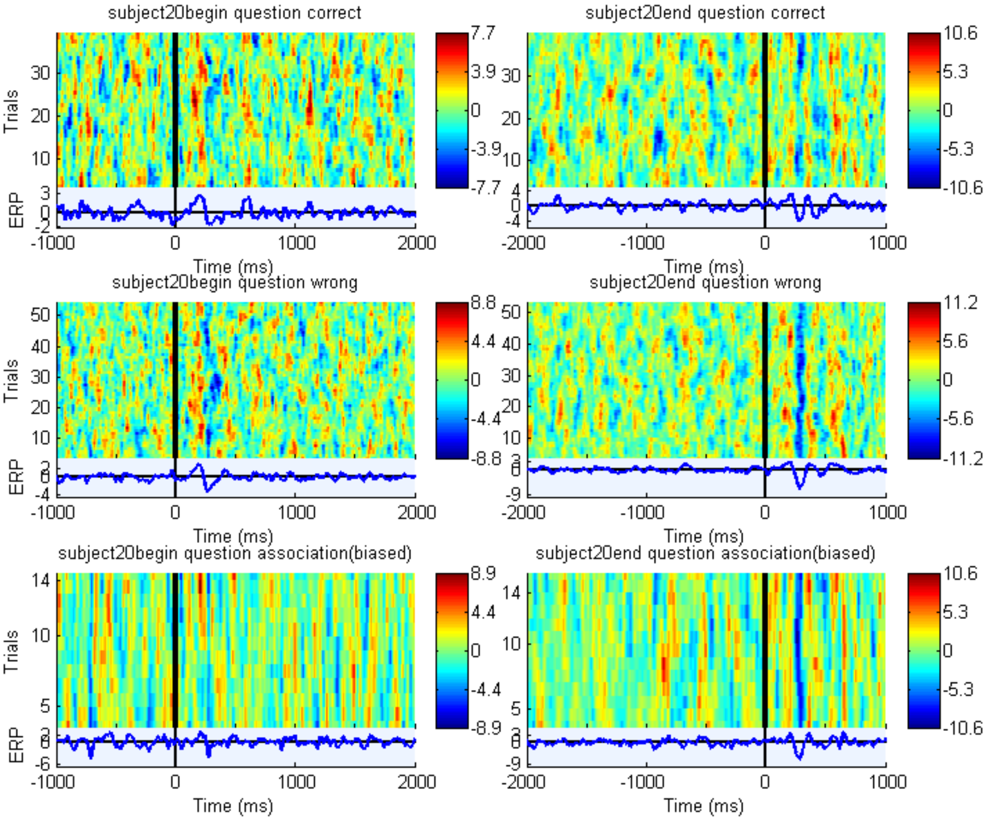

subject12begin question correct
subject12end question correct
subject12begin question wrong
subject12end question wrong
subject12begin question association(biased)
subject12end question association(biased)
Trials
ERP
Time (ms)


subject13begin question correct
subject13end question correct
subject13begin question wrong
subject13end question wrong
subject13begin question association(biased)
subject13end question association(biased)
Trials
ERP
Time (ms)
9.1
4.5
0
-4.5
-9.1
9.2
4.6
0
-4.6
-9.2
10.9
5.4
0
-5.4
-10.9
9.4
4.7
0
-4.7
-9.4
10.2
5.1
0
-5.1
-10.24
8
4
0
-4
-8
-1000
0
1000
2000
-2000
-1000
0
1000


subject15begin question correct
subject15end question correct
subject15begin question wrong
subject15end question wrong
subject15begin question association(biased)
subject15end question association(biased)
Trials
ERP
Time (ms)
8.8
4.4
0
-4.4
-8.8
7.9
3.9
0
-3.9
-7.9
8.7
4.3
0
-4.3
-8.7
7.5
3.7
0
-3.7
-7.5
6.6
3.3
0
-3.3
-6.6
8.1
4.1
0
-4.1
-8.1
-1000
0
1000
2000
-2000
-1000
0
1000


subject18begin question correct
subject18end question correct
subject18begin question wrong
subject18end question wrong
subject18begin question association(biased)
subject18end question association(biased)
Trials
ERP
Time (ms)


subject19begin question correct
subject19end question correct
subject19begin question wrong
subject19end question wrong
subject19begin question association(biased)
subject19end question association(biased)
Trials
ERP
Time (ms)


subject20begin question correct
subject20end question correct
subject20begin question wrong
subject20end question wrong
subject20begin question association(biased)
subject20end question association(biased)
Trials
ERP
Time (ms)