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Investigating the Neuronal Correlates of "Normal" Hallucinations Using Event-Related Potentials (ERPs)

Experimental Research

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Running Title: Neuronal Correlates of "Normal" Hallucinations: An ERP Approach

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Abstract

Visual hallucinations (VH) are often associated with psychiatric, neurological, and ophthalmological conditions but can also occur in healthy individuals, known as “normal” hallucinations (NH). This study investigated the neuronal correlates of NH using event-related potentials (ERPs) recorded during a dual-task paradigm. Fourteen participants completed a task requiring simultaneous judgments of facial orientation and the visibility of a central square, with critical trials designed to induce NH by presenting no stimulus while eliciting perceptual ratings. Behavioral results replicated previous findings, with NH reported in 62.5% of critical trials. Higher visibility ratings in NH correlated with task accuracy and response clarity, suggesting NH involves genuine perceptual experiences influenced by cognitive mechanisms. However, ERP analysis revealed significant limitations in data quality due to the insufficient number of critical trials, leading to high noise levels and low signal-to-noise ratios (SNR), particularly in conditions with NH. While ERPs for the facial orientation task confirmed the recording setup’s reliability, no reliable ERPs were captured for NH due to insufficient statistical power. Future research should focus on optimizing experimental designs by increasing trial numbers, extending session durations, and refining preprocessing methodologies. It is advised to aim for at least 150 trials in future studies while maintaining a focus on improving electrode connectivity to enhance data quality and reliability.

Keywords: normal hallucinations, ERP, EEG, dual-task paradigm, predictive coding, cognitive mechanisms, top-down processing

One of the most notable symptoms in diagnosing psychiatric, neurological, and ophthalmological disorders are visual hallucinations (VH). They are often related to conditions such as schizophrenia, neurodegenerative dementias, eye diseases, delirium, and drug-induced hallucinosis (Abraham & Duffy, 1996; Menon et al., 2003; Collerton et al., 2005; Armstrong, 2012; ffytche & Wible, 2014). Nevertheless, the precise delineation between normal and pathological states remains imprecise (Larøi, 2012; Rodríguez-Testal et al., 2021). Macpherson and Batty (2016) provide comprehensive definition for hallucinations as experiences where an individual perceives an object and its properties, even though no object or its properties exist. According to Collerton and Mosimann (2010) hallucinations can be broadly classified into two categories: simple hallucinations as flashes, dots, geometric patterns, color, and complex hallucinations such as more complicated objects, people, animals, etc.

Experiencing hallucinations is not limited to clinical populations but is also observed in the general population, with prevalence around 28% (van Os et al., 2009; Galdos et al., 2011; Diederen et al., 2012; Laroi et al., 2012; Johns et al., 2014). Although only 25% of these cases meet the criteria for a psychotic disorder (Johns et al., 2002). There are contexts in which healthy individuals experience actually not present objects and it has been shown in terms of laboratory experimental research (Powers et al., 2016, 2017; Aru & Bachmann, 2017; Aru et al., 2018; Vetik et al., 2020). Bachmann (2021) called these experiences as "normal" hallucinations (NH), suggesting that their study could shed light on the foundational mechanisms of attention and awareness and clarify how the perceptual system functions under various conditions. One such study that unexpectedly turned out to be pertinent to this phenomenon was conducted by Mack et al. (2016), where attention was manipulated in a dual-task experimental design originally intended to study phenomenal overflow (cognitive accessibility) in the context of memory. However, later studies by Aru and Bachmann (2017) and Aru et al. (2018) used the dual-task study to show that most participants experienced and reported "normally hallucinated" stimuli that were physically absent.

There are a few contemporary cognitive theories of hallucinations. Based on Helmholtz's idea (1860) that perception is about guessing the causes behind what our senses receive, the predictive coding model provides a detailed framework for understanding how we perceive things (Clark, 2015; Friston, 2005; Hohwy, 2013; O’Callaghan et al., 2017). Originally developed as a data compression strategy in signal processing, predictive coding has been adapted to explain how the brain produces perception by interaction of top-down expectations with bottom-up sensory inputs (Shi & Sun, 1999). This model suggests that

hallucinations appear when the sensory predictions, influenced by top-down processing, have more weight in producing the percept than the actual sensory input. Paradoxically, sometimes the hallucinatory component in cognitive processing may improve veridicality of perception when the percept includes a hallucinatory or misperceived element. For example, a study by Teufel et al. (2015) demonstrated that prior knowledge of a visual scene can increase the recognition of a degraded version of that scene, particularly in individuals at risk for psychosis, emphasizing the influence of top-down processing. This interaction involves top-down mechanisms that help generate stable hallucinatory images, when sensory input falls below bottom-up sensory threshold and does not provide enough detail or information to override the brain's assumptions (Powers et al., 2016).

Furthermore, the Perception Attention Deficit (PAD) model that was developed by Collerton McKeith and Perry (2005) suggests that hallucinations appear when the brain mistakenly focuses on the wrong set of proto-objects within a scene and gets weak perceptual signals. In that case, mind is unable to bind proto-objects (visual elements, such as edges, color, movement) with each other properly and mistakenly perceives them as contextually plausible reality. This model finds empirical support in research of neurodegenerative and ophthalmological disorders, indicating its plausibility (Collerton & Mosimann, 2010). In support of this theory, Aru et al. (2018) in their experiments emphasize that individuals often experience hallucinations in dual-task situations where attention is split between multiple stimuli and different tasks. That happens specifically when attention is directed toward an object different from another, task-irrelevant object that becomes associated with it. This dynamic is further supported by evidence showing that expectations can significantly bias perception when attention is diverted from the primary stimuli (Aru & Bachmann, 2017).

Hallucinations as a phenomenon has been widely studied using techniques such as positron emission tomography (PET), functional magnetic resonance imaging (fMRI) and computer tomography (CT) to answer questions about its physiology (Allen et al., 2008). Nevertheless, these methods do not capture the fast changes in brain activity well because they lack fine temporal resolution. This makes it hard to fully understand what are the fine-scale temporal processes in the brain that underlie hallucinations therefore limiting insights into the causes of visual hallucinations in temporal dynamics. In contrast, techniques like electroencephalography (EEG) can reveal detailed stages of brain activity with high temporal resolution both during rest and more complex mental tasks, capturing events as they happen. Event-related potentials (ERPs) from EEG recordings could tell us more about neural activity during NH by analyzing latency and amplitude of brain waves of bioelectric activity during

specific sensory or cognitive tasks. Consequently, we can register the instance of NH appearance within a short post stimulus time epoch and show how much and how fast different brain regions become involved in this process. We can also explore whether NH are especially sensitive to certain brain wave frequencies. Moreover, the exploration of top-down processes through the lens of ERPs presents a unique opportunity to understand the brain's role in modulating perception based on expectations, prior knowledge, attention, and therefore understanding hallucinations (daSilva Morgan et al., 2018). Although visual hallucinations have been studied in conditions like dementia with Lewy bodies (DLB), Alzheimer's disease (AD), and Parkinson's disease dementia (PDD) using the ERP method, these investigations focused more on studying how these patients process visual information and perform cognitive tasks rather than the hallucinations themselves (daSilva Morgan et al., 2018).

The purpose of the present study is to explore whether there are differences in event-related potentials (ERPs) recorded during the episodes of "normal" hallucinations induced by a behavioral experiment, as originally conducted by Aru et al. (2018) in Experiment 2b. During the experiment, participating experimental subjects perform the dual-task, which consist of a primary and an additional (auxiliary) task. In the first, individuals need to decide whether two faces displayed bilaterally on the screen have the same orientation (inverted, non-inverted) or not, while focusing on the center square object. In the secondary task subjects had to evaluate the level of visibility of the central square object, while performing primary task. In some trials there was no central object; in these “critical” trials NH of the square object is expected to occur. In my study the EEG of brain activity will be recorded during the above described behavioral task. ERPs as markers of real stimulus processing and possibly also NH experience will be extracted from the EEG recording. This research investigates the neural dynamics underpinning visual processing involving episodes of hallucinatory experiences in non-clinical populations. As no pertinent ERP data gathered in this kind of experimental situation exist, the present study belongs to exploratory research. Consequently, this work aims to address the following main questions: (1) Does the experiment replicate the behavioral results reported in Aru et al. (2018)? (2) What are the effects of visibility ratings in critical trials on reaction times (RT)? (3) Can the generated ERPs and their details be reliably captured in individuals experiencing “normal” hallucinations, considering the statistical power calculated for the behavioral results in Aru et al. (2018)? To control whether the EEG/ERP method used is sensitive enough for recording brain responses to visual signals, the ERPs of trials with primary face task are analyzed (4) If captured, are there any observable differences in mean amplitudes when comparing the ERPs of trials with experience of NH to the ERPs of trials without NH.

Method

Subjects

The target group is volunteers who are of legal age, healthy, right-handed, with normal or corrected-to-normal vision. The invitation was distributed through social media platforms (Facebook, Instagram) and via physical posters to avoid sampling psychology students, as they might better guess the object of the study due to their prior knowledge of experimental paradigms. In addition, volunteers from the researcher's circle of acquaintances were involved in the invitation. The effect sizes reported in Aru et al. 2018 and the G.Power 3.9.6 application were used to define the minimum number of participants for the study where NH could emerge. It suggests a minimum number of participants of 9 (a = 0.05; 1-b prb = 0.8; d = 1.08), but I intend to recruit 14 participants to increase statistical power and internal validity.

14 participants (7 male, 7 female) participated in the experiment. Participant ages ranged from 19 to 23 years old (M = 20.43, SD = 1.28). All participants were non-psychology students, were unaware of the object of the study, and met the following selection criteria:

- are of legal age (18 years or older);
- are right-handed;
- have normal or corrected-to-normal vision (glasses or contact lenses if necessary);
- have no diagnosis of migraine, epilepsy, seizures, stroke, stroke, hypertension, cardiac arrhythmia or mental health disorder;
- have no metal implants in their head or braces;
- have a stimulator, hearing aid, implant or therapy pump;
- have not used drugs or psychotropic substances, including caffeine-containing beverages (coffee, Coca-Cola, etc.), for at least 6 hours prior to experiment.

Ethics Committee Approval

For conducting the study experiment, the approval from University of Tartu Research Ethics Committee was obtained (Protocol number: 390/T-169). Prior to the experiment the informed consent was given to each subject, informing about the research methodology, response indications and potential risks of harm. Participation in the study was voluntary and the subject has the right to refuse or discontinue participation. Since the Euro-standard

equipment we used (Nexstim eXimia EEG system) is certified and patented as having no adverse health effects, and since tests in Finland, the USA, Germany, Japan and elsewhere have shown no adverse effects, I can be reasonably confident in its safety of use.

General Experimental Design

In all experiments the participants were confronted with a dual task in the main block where one task was the “main task”, the other task the “auxiliary task”. On 90% of the trials the participants were prompted for perception in the main task, but they were explained from the outset that the auxiliary task is also relevant. In the learning phase both the main task and the auxiliary task was separately run before the dual task condition. Subjects were fitted with the EEG cap before the perception task. Participants were debriefed about their experience after the experiment and asked if they had noticed the missing stimuli.

Apparatus

The experiment was conducted in the experimental psychology laboratory of the UT Institute of Psychology (Tartu, Ravila 14a). Although this experiment uses EEG equipment, the planned experiment is based on a specific behavioral paradigm taken from research (Aru et al., 2018). The behavioral aspect of the experiment (i.e. the task the subject has to solve) is prepared in Python programming language and driven by the VisionEgg software. For the computer-controlled experimental display a SUN CM751U CRT monitor with 1024 × 768 pixels resolution and 100 Hz refresh rate was used, which ensures accurate timing and quality of stimuli.

To measure EEG data, the experiment used a Nexstim eXimia EEG system equipped with 60 channels for active electrodes (Nextim Ltd., Finland). A special EEG hat with 60 carbon electrodes with 10-20 montage system was placed on the subject's head and a special certified gel was used to increase the sensitivity of the electrodes. The EEG signals were recorded using a dedicated reference electrode placed on the forehead (frontal referencing), which allows for consistent signal quality across all channels. To monitor and eliminate artefacts, in addition to the EEG data, eye movement signals were recorded using two horizontal HEOG electrodes placed approximately 10 mm from the outer corners of each eye. The 22 electrodes, including Iz, O1, Oz, O2, PO3, POz, PO4, P7, P3, P1, Pz, P2, P4, P8, Cz, F7, F5, F1, Fz, F2, F6, and F8, were used as active electrodes (ROI). Thus, the ROI sample

covers the main visual areas and the frontal cortex areas involved in top-down cognitive control.

Procedure

Prior to the experiment, the subjects were provided with an informed consent form containing essential information on the purpose of the experiment, the procedures and the measures to ensure confidentiality. The name and purpose of the experiment were deliberately disguised in the consent form so that the subjects were naïve to the specific hypotheses of the study. This helps to avoid bias and the influence of expectations on the results, thus ensuring more objective and reliable data. The consent form stresses that participation is completely voluntary and that anyone can withdraw from the experiment at any time. It also confirmed that the data collected will be treated confidentially and are for scientific use only. After signing the written consent to participate an orientation and practice session was run, in which the participants completed 30 practice trials for each task separately, so that they familiarized themselves with the test tasks and the positioning of the response buttons.

The task lasted approximately 15 minutes and consisted of three blocks of 80 trials each with pauses in between. In all experiments the observers viewed stimuli from the distance of 80 cm. Each test started with a 1 second fixation cross on a grey background to help focus and keep eye fixation. Then, for 100 milliseconds, two faces (1.7 degrees of visual angle) appeared simultaneously on the left and right sides of the screen, positioned 300 pixels away from the center of the screen. Face stimuli used in experiment were selected from the Radboud Faces Database (Langner et al., 2010). All images were transformed to grayscale and resized to fit a round shape of uniform size, removing the hairline and leaving only the facial area visible. The faces were presented in four different configurations: both faces upright, both faces inverted, left face upright and right face inverted, and left face inverted and right face upright. **Figure 1** illustrates the stimulus display and response screen.

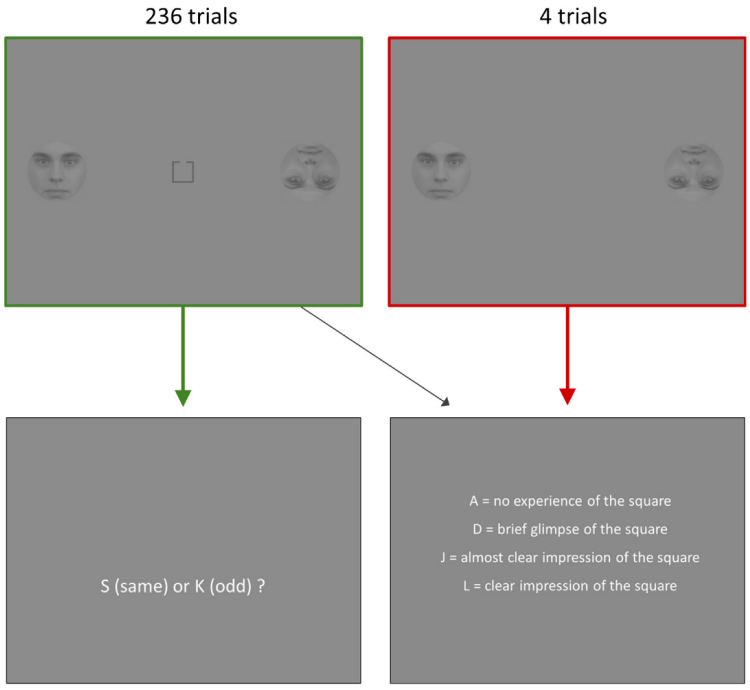

Figure 1. The display featured two faces and a central Landolt square for two tasks: participants judged face orientation congruence or rated Landolt square visibility. In single-task conditions, tasks were trained independently, while in dual-task conditions, participants prepared for both tasks, focusing on faces in 90% of trials to divert attention from the faint Landolt stimulus. In 10% of trials, subjects rated Landolt square visibility on a four-point PAS. In four critical trials, the Landolt square was absent, but subjects still rated perceptual clarity.

Facial stimulus presentation was accompanied by the appearance of a small grey Landolt-type square, which replaces the fixation cross and subtends 0.5 degrees of visual angle. Subjects were asked to maintain fixation during each individual trial. After 700 milliseconds from the presentation of the stimuli, a response screen appeared. 90% of the trials required deciding whether two faces were in the same orientation (both upright or both inverted) or in different orientations (one upright, one inverted). In the remaining 10% of the trials, subjects were asked to rate the visibility of the Landolt square on a four-point perceptual awareness scale (PAS). In the four critical trials, the Landolt square was not presented, but subjects were nevertheless asked to rate the perceptual clarity using the keys A, D, J, L on the keyboard corresponding to the perceptual levels "no perceptual awareness of the stimulus", "barely noticeable stimulus appearance", "almost clear perception of the stimulus", "clear perception of the stimulus". These critical trials were presented only in second and third block, ensuring that attention was set to be diverted away from the faint Landolt stimulus. The illusory perception score is

obtained by summing the visibility ratings of all critical trials. The computer program controlled the timing of the visual stimuli and recorded participants' responses.

EEG preparation

Due to the requirements for EEG experimenting the experiments were performed (i) by an experimenter who has been thoroughly instructed beforehand, (ii) only after a preliminary check of the condition of the apparatus (including a grounding check). As the fitting of the EEG hat can take up to three quarters of an hour, the subjects were warned about this and given the opportunity to withdraw both before and during the experiment if they feel uncomfortable. To ensure contact of the EEG electrodes, a preparation was performed by pushing aside the hair under each electrode with a fine stick. The scalp is then cleansed of dead skin cells and grease with an exfoliating saline gel. The subject was warned that scalp cleaning may cause a slight scratching sensation and if this was the case, it had to be reported, and the experimenter ensured that there was no discomfort. Finally, the opening at the electrode is filled with certified saline gel to ensure a sufficiently good connection between the scalp and the electrode. EEG preparation took up to three quarters of an hour (considering an ROI of 22, + 2 eye electrodes). As the saline gel used in the preparation is lubricating to the hair, the subjects had the opportunity to wash their head after the test was completed. Only cleaned/washed electrode caps were used.

EEG recording

Throughout the experiment, the EEG was recorded along with stimulus timing markers to monitor real-time brain activity and event-related components of the experiment. The data of 13 participants out of 14 were recorded, as the data of one participant were not recorded due to a technical problem. The time required to complete the EEG recording session varied between 12 and 15 minutes, depending on the pauses taken by participants and their response speed during the tasks. EEG data were recorded at a sampling rate of 1450 Hz with no online filters applied; this is in order to preserve the raw signal for offline preprocessing. The resistance of the electrode-to-skin connection was maintained below 15 kΩ, as recommended for optimal EEG signal quality, and the quality of the EEG connections was continuously monitored throughout the test. If an electrode connection was lost or its signal became too noisy, the preparation procedure was repeated during a pause. While during the impedance evaluation procedure, approximately 25% of the electrodes were indicated as having 'poor'

signal quality (marked in red by the recording software), primarily due to slight gaps between the EEG cap and the scalp in areas with sparse contact caused by hair or anatomical variations, the remaining 75% of electrodes provided good to excellent signal quality, ensuring reliable data acquisition for subsequent analysis.

EEG preprocessing and artefact correction

During EEG preprocessing, raw data were processed using MNE Python (1.8.0). A bandpass filter was applied between 0.1 and 30 Hz to each participant’s recording to attenuate slow drifts and high-frequency noise. The filtering process was conducted ensuring optimal signal preservation for subsequent analyses. No additional re-referencing was applied during preprocessing because frontal referencing was employed during the recording process, with a dedicated reference electrode positioned on the forehead. For statistical analysis of ERP components, clusters of parietal-occipital ROI (Iz, O1, Oz, O2, PO3, POz, PO4, P7, P3, P1, Pz, P2, P4, P8) and frontal ROI (F7, F5, F1, Fz, F2, F6, F8) were selected for analyzing visual (bottom-up) and cognitive (top-down) processes. After initial filtering, Independent Component Analysis (ICA) was applied to identify and remove artifacts from the EEG data, such as eye blinks and muscle artifacts. ICA decomposition was performed for each participant, specifying 20 components for decomposition. Artifact-prone components were identified through visual inspection based on topographies. Eye blink artifacts, typically robust in the frontal regions, were specifically targeted and removed. Muscle artifacts, most frequently observed in lateral and temporal regions, and general noise, which often appeared uniformly across the electrode array due to systemic recording issues, were also identified and removed during the preprocessing steps. The number of components identified as artifacts ranged from 2 to 6 per participant, depending on the individual participant’s data.

EEG Epoching

Each participant’s EEG data was segmented into epochs ranging from 200 ms before stimulus onset to 800 ms after stimulus presentation. Baseline correction was applied using the pre-stimulus 200 ms interval to account for inter-trial variability.

Statistical Analysis

For behavioral data, JASP (Version 0.19.1) was used for statistical analysis. Student Paired t-tests were conducted to evaluate mean differences in Average Visibility Ratings across conditions. Pearson correlations were used to examine the relationship between illusory perception scores and average visibility ratings. One-way ANOVAs and post hoc tests assessed the interaction between visibility ratings and reaction times (RTs) in critical trials with no stimuli (hallucination condition). Additionally, independent samples t-tests were used to investigate RT differences between correct and incorrect responses in the face orientation discrimination task. All tests were conducted at a significance level of $\alpha \leq 0.05$, and effect sizes were reported using Cohen's *d*.

For EEG data, statistical analyses were performed using the latest available version of MNE Python (1.8.0). Supporting libraries, including NumPy and Matplotlib, were used for data manipulation and visualization. Grand average ERPs were computed for each condition of interest. Subsequent mean amplitude comparisons were performed on Grand Average ERPs to evaluate differences between conditions. As the chosen time windows were: (1) not normally distributed based on skewness and kurtosis, and (2) histogram analysis revealed outliers in the data distribution, a non-parametric, two-tailed Wilcoxon Signed-Rank Test was selected to compare mean amplitudes across ERP conditions. While it is a more conservative alternative to parametric tests, a significance threshold ($\alpha = 0.1$) was employed to account for compensatory and exploratory purposes. Holm correction was applied to minimize Type I error due to multiple comparisons, which ranged from 3 to 8 per condition. Effect sizes were reported using rank-biserial correlation. Specifically, the analyses focused on two comparisons: (i) Face Orientation Discrimination Task consisting of trials of correct face perception vs. incorrect face perception and (ii) Square Visibility Task consisting of hallucinated trials vs. non-hallucinated trials. First comparison was included to confirm that the EEG recording setup was responsive to the stimuli presentation and capable of capturing typical ERP patterns. The test analyzed components including N1/N170, P2, and P3 for the frontal ROI and P1, N1/N170, P2, and P3 for the parieto-occipital ROI. In second comparison, the data were divided into eight separate 100 ms time-locked windows post-stimulus, and the Wilcoxon Signed-Rank Test was conducted within each of these windows to evaluate mean amplitude differences between conditions. An additional power analysis based on SNR (Signal-to-noice-ratio) was conducted for condition with hallucinatory experience to provide framing for future studies.

Results

Behavioral Data

Participants quite often reported illusory perception: on the critical trials where the square was absent, only one participant never (i.e. on none of the 4 trials) used a visibility rating higher than 1 ("no experience of the stimulus"), but five participants reported illusory perception every time (i.e. on each of the 4 trials). Nine of the 14 participants saw illusory perception on more than three occasions. Eleven participants at least once used the rating 3 "almost clear expression ..." for the absent stimulus. On an average of 62.5% of critical trials (mean across participants) at least some experience (i.e. a visibility rating higher than 1) of the missing stimulus was reported (Figure 2). This replicates the earlier results on "normal" hallucination (Aru et al., 2018). Additionally, participants were generally accurate in detecting changes in the primary face task, with 87.9% of responses being correct. This satisfies the necessity that subjects payed required attention to the face task.

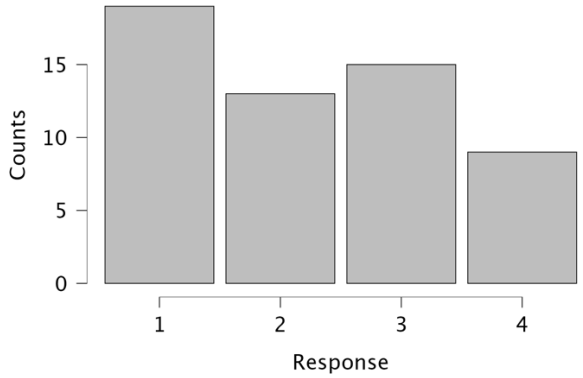

Figure 2. Proportion of visibility ratings given in critical trials.

We observed a strong positive correlation between the illusory perception score in critical trials where central stimuli was absent and the average visibility rating in trials with stimuli present ($r = 0.87$, $p < .001$).

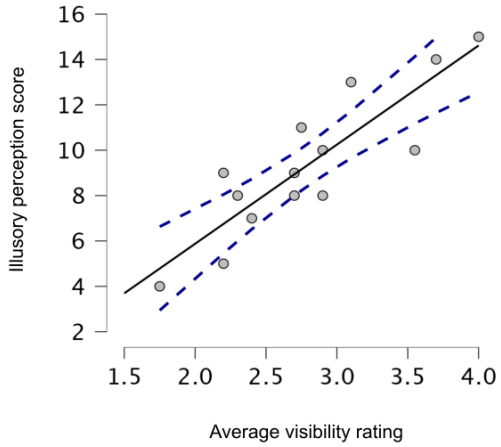

Figure 3. Correlation between average visibility rating in non-critical trials and illusory perception score with 95% confidence interval.

There was also a significant difference between visibility ratings provided for trials when the square was present compared to when it was absent, $t(13) = 4.42$, $p < .001$, $d = 1.18$ (**Figure 4**). The average rating for non-critical trials was 2.80 (SD = 0.63), while for critical trials it was 2.34 (SD = 0.79). This result suggests that at least some part of the responses reporting visibility of the non-present stimulus were true hallucinations and not merely guesses or biased positive responses without a corresponding hallucinated experience.

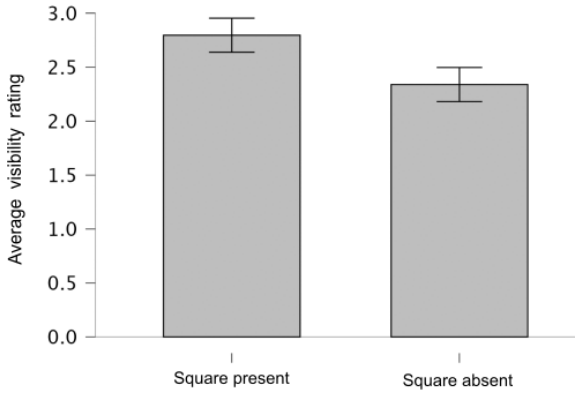

Figure 4. Paired T-test results for conditions with square present and absent.

Also, a moderate trend for positive correlation between the illusory perception score and the number of correct answers in the primary face task was observed, although this was not statistically significant ($r = 0.41$, $p = 0.15$; Figure 5)

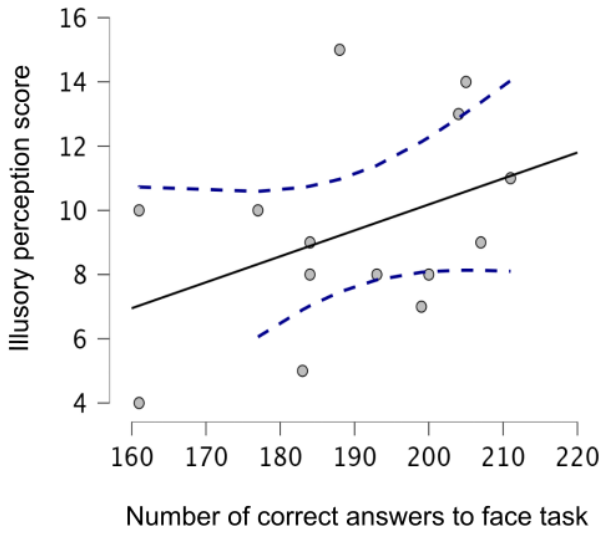

Figure 5. The graph showing insignificant moderate positive correlation between number of given correct answers to primary face task and illusory perception score.

A one way ANOVA was conducted to examine the effect of visibility rating in critical trials with no stimuli on reaction time across four conditions: (1) no perceptual awareness of the stimulus, (2) barely noticeable stimulus appearance, (3) almost clear perception of the stimulus, and (4) clear perception of the stimulus. There was a significant effect of visibility rating among the conditions at the $p < .05$ level, $F(3,52) = 3.97$, $p = .013$. LSD post hoc comparisons revealed significant differences between some conditions. Specifically, participants in the "barely noticeable stimulus" condition ($M = 3.42$, $SD = 1.13$) had significantly slower reaction times compared to those in the "clear perception" condition ($M = 2.30$, $SD = 0.62$) and the "no perceptual awareness" condition ($M = 2.64$, $SD = 0.75$) (**Figure 6**). However, there were no significant differences in reaction times between other pairs of visibility ratings, including conditions 1 and 3, 1 and 4, as well as conditions 2 and 3. All in all, these results suggest that in trials with no hallucination and with relatively clear hallucinations subjects decided for their clarity rating faster, but in the very weak hallucinatory experience trials it took longer to produce the rating.

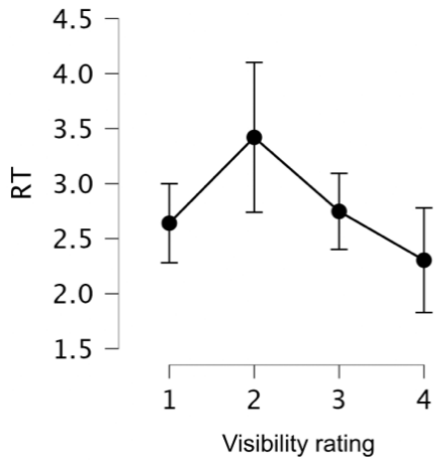

Figure 6. One-way ANOVA analysis related descriptive statistics for reaction time as a “function”of visibility rating in critical trials.

Independent samples t-test was conducted to examine the difference in reaction times between correct and incorrect responses in the primary face task (**Figure 7**). The results indicated a significant difference in reaction time based on response accuracy, $t(3018) = 9.46$, $p < .001$, $d = 0.527$. Participants who answered correctly had a faster average reaction time ($M = 1.37$, $SD = 0.63$) compared to those who answered incorrectly ($M = 1.77$, $SD = 1.41$). This is a standard result from perception tasks, which helps conclude that subjects followed the task with sufficient care and kept their focus.

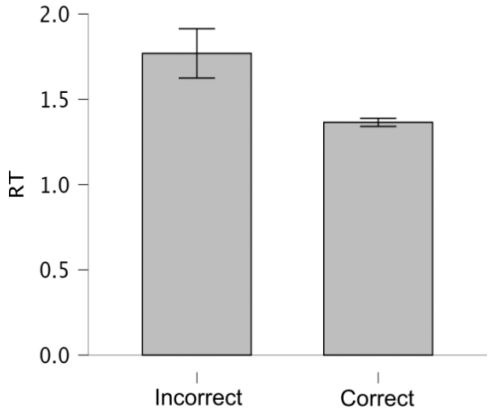

Figure 7. The diagram showing the results of an independent T-test for difference between reaction time in the correct and incorrect face matching trials in the primary face task.

EEG data

Face Orientation Discrimination Task ERP. The data of 13 participants were used to compute Grand average ERPs for the correct face perception condition (Face Correct) and the incorrect face perception condition (Face Error). The Grand ERP comparison for both frontal and parieto-occipital ROIs included 2436 trials in the correct face perception condition, where participants correctly identified the orientation of faces, and 358 trials in the error condition, where participants responded incorrectly.

Figure 8 represents Grand average ERP waveform comparison for face correct vs. incorrect perception in frontal ROI across 13 participants. For the frontal ROI (F7, F5, F1, Fz, F2, F6, F8), visual inspection of the grand ERPs confirmed that the EEG recording setup effectively captured typical ERP components associated with the face orientation task in response to stimulus presentation. However, the error condition demonstrated noisier and less stable waveforms, likely due to the reduced sensitivity of frontal electrodes to low-amplitude signals and the relatively small number of trials compared to the correct condition. Despite these limitations, the correct condition provided sufficient data to reliably identify ERP components. In what follows the qualitative and amplitude-descriptive analysis of the common types of ERP components will be presented. SNR (signal-to-noise ratio) analysis revealed a moderate estimated value of 3.04 for the Face Correct condition and a low estimated value of 0.70 for the Face Incorrect (Error) condition, indicating a high prevalence of noise in the frontal electrodes for latter condition.

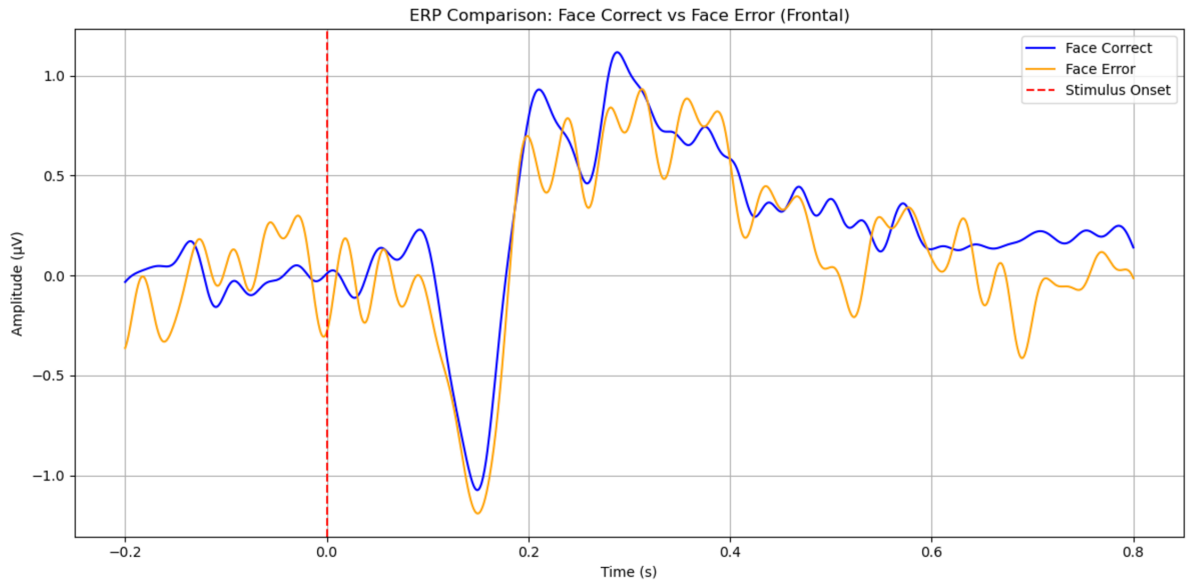

Figure 8. Grand ERP waveform comparison for face correct vs. incorrect perception in frontal ROI across 13 participants.

A negative peak in response to visual stimulus observed within the 100–180 ms time window, with amplitudes of -1.11 μV (SD = 0.26 μV) in the correct condition and -1.22 μV (SD = 0.18 μV) in the error condition, likely corresponds to the N1 component, which is linked to early perceptual processing, sensitivity to discrimination tasks, and spatial attention (Vogel & Luck, 2000), but also possible that it substantially overlaps with N170 component assumed to be a face perception marker, although the N170 is more commonly associated with activity at PO and P electrodes.

The positive deflection observed within the 180–230 ms time window, peaking at 0.94 μV (SD = 0.25 μV) in the correct condition, likely corresponds to the P2 component and therefore is associated with attentional categorization and stimulus evaluation (Luck, 2014). The observed P2 component, as the most plausible candidate, aligns with expectations. Participants were tasked with categorizing stimuli into two distinct groups, "SAME" and "DIFFERENT," thereby engaging attentional categorization processes, as reflected by this component. Moreover, in the context of our study, along with the possible N170, the P2 component could play an important role in the evaluation of second-order facial information and has been shown to exhibit higher amplitudes for prototypical faces (Reinke et al., 2024). This aligns with our study, as the face images used in the experiment, sourced from the Radboud Faces Database (Langner et al., 2010), depicted Caucasian males and females, which are prototypical for the participants in this study. In the error condition, the peak amplitude within the same time window was 0.78 μV (SD = 0.22 μV). However, due to the noisier and

less stable waveforms in the error condition, it is difficult to draw definitive conclusions about the P2 component. Finally, the P3 component, reflecting cognitive processes such as stimulus evaluation, decision-making, and memory updating (Picton, 1992), was identified within the 280–340 ms time window. The peak amplitude for P3 in the correct condition was 1.13 μV (SD = 0.16 μV). In the error condition, while it was challenging to reliably distinguish a clear P3 peak due to noise, the observed amplitude was 1.05 μV (SD = 0.14 μV), suggesting reduced stability and signal clarity. So far, the results showed that the typical ERP components recorded in visual perception tasks emerged also in my study. But what about differences between correct response and incorrect response trials?

A Wilcoxon Signed-Rank Test revealed no statistically significant differences in mean amplitudes for the N1/N170, P2, and P3 components in frontal ROI. The results, along with mean amplitudes and standard errors (SE) for each condition, are presented in Table 1. No significant differences in mean amplitudes were observed among the components. However, a large effect size was observed, which may have been influenced by noise and the insufficient number of trials in the error condition. Notably, the P2 and P3 components showed p-values slightly higher than the alpha level, suggesting the possibility of some differences. However, these results remain inconclusive and should be interpreted with caution due to the imbalance in trial counts between conditions.

Table 1

Wilcoxon-Signed Rank Test Results for Face Orientation Task (Frontal ROI) Across ERP Components

Component	Mean COR (μV)	SE COR(μV)	Mean INCOR (μV)	SE INCOR (μV)	Z value	Effect Size	Adjusted p*
N1/170	-0.551	0.110	-0.724	0.085	-2.023	-0.905	0.188
P2	0.692	0.112	0.487	0.134	-2.023	-0.905	0.125
P3	0.926	0.067	0.744	0.077	-1.753	-0.784	0.125

Note. COR - Correct Face Perception, INCOR - Incorrect (Error) Face perception, *Rank-Biseral Correlation, *Holm correction

For the parieto-occipital ROI (O1, Oz, O2, PO3, POz, PO4, P7, P3, P1, Pz, P2, P4, P8), the EEG recording setup effectively captured the expected ERP components in response to stimuli presentation during the face orientation task for both conditions. SNR (signal-to-noise ratio) analysis revealed a high estimated value of 11.19 for the Face Correct condition and a

moderate estimated value of 3.64 for the Face Incorrect (Error) condition, indicating an adequate signal-to-noise ratio necessary for reliable ERP measurement. **Figure 9** represents Grand average ERP waveform comparison for face correct vs. incorrect perception in parieto-occipital ROI across 13 participants. First, the qualitative description of the ERP components is what follows.

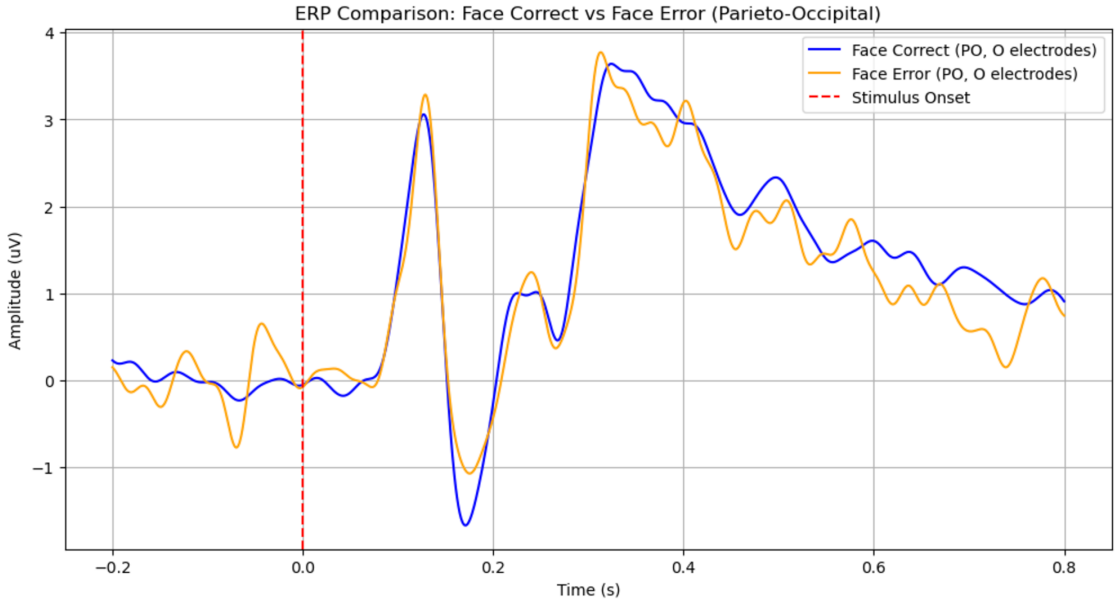

Figure 9. Grand ERP waveform comparison for face correct vs. incorrect (error) perception in parieto-occipital ROI across 13 participants.

Similar paradigms investigating face processing in peripheral vision have also analyzed the P1 component in parieto-occipital electrodes (Kovács et al., 2017; Wang et al., 2022). Consistently, the P1 component, which reflects early visual processing (Luck, 2014), was identified within the 90–140 ms time window. The peak amplitude for P1 in the correct condition was 3.08 µV (SD = 1.22 µV), while in the error condition it was 3.30 µV (SD = 1.17 µV).

A negative peak observed within the 160–200 ms time window is assumed to correspond to the face-specific N170 component, as this was the focus of studies using similar paradigms (Kovács et al., 2017; Wang et al., 2022). The peak amplitude of the N170 component in the correct condition was -1.68 µV (SD = 0.12 µV), while in the error condition it was -1.12 µV (SD = 0.36 µV). The P2 component, associated with attentional categorization, was evident within the 200–270 ms time window. The peak amplitude for P2 in the correct condition was 1.15 µV (SD = 0.38 µV), compared to 1.30 µV (SD = 0.53 µV) in the error condition. Finally, the P3 component, linked to higher-level cognitive processes such as stimulus evaluation and decision-making, was present within the 290–350 ms time window. The peak amplitude for P3

in the correct condition was 3.68 μV (SD = 0.56 μV), while in the error condition it was 3.79 μV (SD = 0.60 μV).

A Wilcoxon Signed-Rank Test revealed no statistically significant differences between correct and incorrect trials in mean amplitudes for the P1, N1/N170, P2, and P3 components in the Face Orientation Task for the parieto-occipital ROI. The N1/N170 component demonstrated a large effect size but did not pass the Holm correction. The adjusted p-value, slightly above the alpha level, suggests a potentially valid effect; however, result remains inconclusive and need to be interpreted with caution. The results, along with mean amplitudes and standard errors (SE) for each condition, are presented in **Table 2.**

Table 2

Wilcoxon-Signed Rank Test Results for Face Orientation Task (Parieto-occipital ROI) Across ERP Components

Component	Mean COR (μV)	SE COR (μV)	Mean INCOR (μV)	SE INCOR (μV)	Z value	Effect Size	Adjusted p*
P1	1.728	0.208	1.738	0.265	-0.734	-0.300	1.000
N170	-1.234	0.053	-0.866	0.161	-2.201	-0.899	0.125
P2	0.736	0.268	0.638	0.235	-0.944	-0.385	1.000
P3	3.197	0.406	3.184	0.415	-0.315	-0.128	0.844

Note. COR - Correct Face Perception, INCOR - Incorrect (Error) Face perception, *Rank-Biseral Correlation, **Holm correction

Square visibility Task ERP. The data from 13 participants were used to compute the Grand Average ERP for the critical *non-hallucination* condition, in which Landolt-type stimuli were presented and participants rated their visibility. To compute Grand average ERP for *hallucination condition*, where participants reported illusory perception in the absence of stimuli, the data of 12 participants was used, as one participant has never experienced hallucinatory effect (i.e. on none of the 4 critical trials used a visibility rating higher than 1). Grand average ERP comparisons were aquired for both frontal and parieto-occipital ROI and included 257 trials for the critical non-hallucination condition (Critical) and 33 trials for hallucination condition (Hallucination).

Figure 10 shows the Grand Average ERP comparison for the critical-trial non-hallucination condition (13 participants) and the critical-trial hallucination condition (12 participants) for frontal ROI (F7, F5, F1, Fz, F2, F6, F8). Visual inspection of the hallucination

condition did not reveal distinct peaks due to insufficient number of trials. While the critical-trial condition without hallucination demonstrated more consistent signals, some fluctuations were also observed, suggesting that the number of trials in this condition may also have been insufficient. The observed baseline noise suggests that the power for the condition was insufficient, particularly for the hallucination condition. SNR (signal-to-noise ratio) analysis revealed a low estimated values of 1.56 and 0.41 for the Critical and Hallucination condition, indicating a high prevalence of noise in the frontal electrodes for both conditions. Nonetheless, visual inspection of the critical conditions revealed near-distinct peaks within the specified time windows, indicating some neural responses to stimulus presentation. Within the 120–180 ms time window, the peak amplitude for the critical-trial condition without hallucination was -1.02 µV (SD = 0.55 µV). In the 200–230 ms time window, the peak amplitude was 0.69 µV (SD = 0.27 µV), and within the 260–300 ms time window, the peak amplitude was 1.03 µV (SD = 0.30 µV).

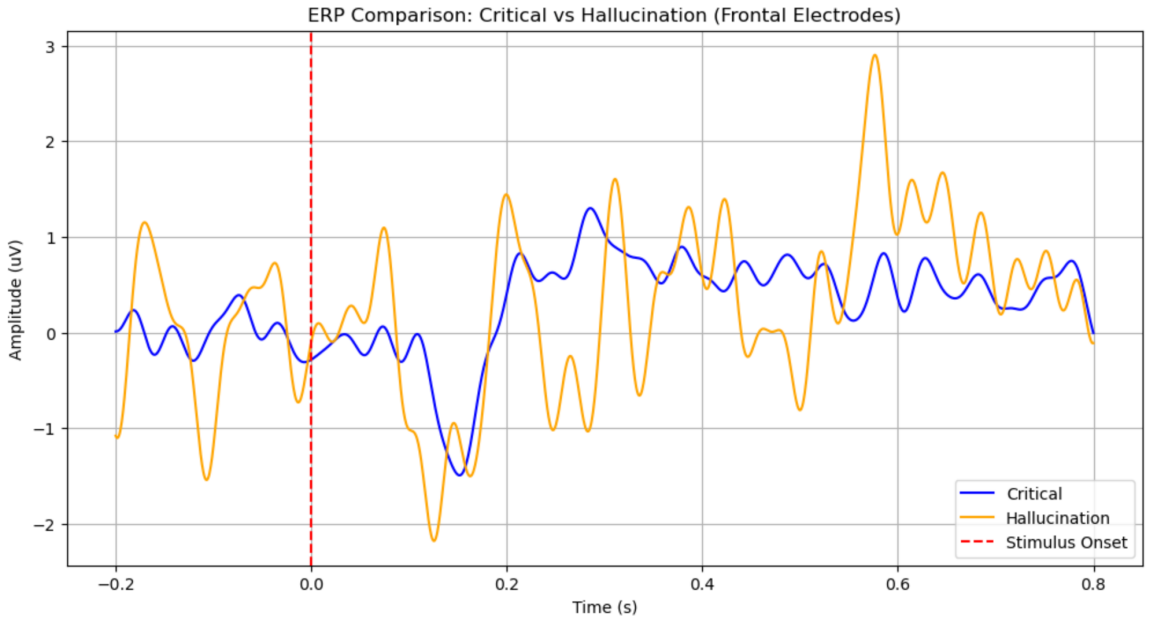

Figure 10. Grand Average ERP for the critical-trial non-hallucination condition ("Critical", 13 participants) and the critical-trial hallucination condition ("Hallucination", 12 participants). Data from Frontal electrodes.

Wilcoxon Signed-Rank Test results for mean ERP amplitudes revealed no statistically significant differences across 100 ms time windows in the Square Visibility Task for the frontal ROI. **Table 3** provides the results, along with mean amplitudes and standard errors (SE) for each condition. Although the 200–300 ms, 500–600 ms, and 600–700 ms windows demonstrated large effect sizes, none of the tests passed the Holm correction. The high noise

levels and limited number of trials make it difficult to draw reliable conclusions about peaks, increasing the likelihood of false positives.

Table 3

Wilcoxon-Signed Rank Test Results for Mean ERP Amplitudes Across 100 ms Time Windows in the Square Visibility Task (Frontal ROI)

Time Window	Mean CR (μV)	SE CR(μV)	Mean HL (μV)	SE HL(μV)	Z value	Effect Size*	Corrected p**
0-100 ms	-0.135	0.088	0.161	0.094	-2.028	-0.767	0.235
100-200 ms	-0.631	0.131	-0.934	0.265	-1.352	-0.511	0.657
200-300 ms	0.793	0.043	-0.109	0.209	-2.366	-0.894	0.128
300-400 ms	0.759	0.076	0.637	0.291	-0.169	-0.064	1.000
400-500 ms	0.616	0.124	0.237	0.116	-1.521	-0.575	0.624
500-600 ms	0.500	0.101	1.053	0.093	-2.366	-0.894	0.128
600-700 ms	0.487	0.131	1.158	0.184	-2.366	-0.894	0.128
700-800 ms	0.434	0.153	0.469	0.108	-0.338	-0.128	1.000

Note. HL - Hallucination Condition, CR - Critical Condition, *Rank-Biseral Correlation, **Holm correction

For the parieto-occipital ROI (O1, Oz, O2, PO3, POz, PO4, P7, P3, P1, Pz, P2, P4, P8), the hallucination condition showed irregular and noisy waveforms with large baseline fluctuations, suggesting insufficient power for reliable comparisons. Visual inspection of the hallucination condition did not reveal distinct peaks due to insufficient number of trials. SNR (signal-to-noise ratio) analysis revealed low estimated values of 2.79 and 2.37 for the Critical and Hallucination condition, respectively, indicating a high prevalence of noise in the parieto-occipital electrodes for both conditions.

Figure 11 shows the Grand Average ERP comparison for the critical non-hallucination condition (13 participants) and the critical hallucination condition (12 participants) for parieto-occipital electrodes. While some waves aligned with the critical condition, it was difficult to determine whether they represented distinct peaks or random noise, particularly around the 100 ms time window. In contrast, the critical-trial condition with no hallucination displayed more distinct peaks, though fluctuations were still observed, likely due to averaging across an insufficient number of trials. For the critical-trial no hallucination condition, the following peak amplitudes and standard deviations (SD) were identified: within the 80–130 ms time window,

the peak amplitude was 0.86 µV (SD = 0.62 µV); within the 150–180 ms time window, the peak amplitude was -1.83 µV (SD = 0.42 µV); and within the 320–370 ms time window, the peak amplitude was 3.58 µV (SD = 0.77 µV).

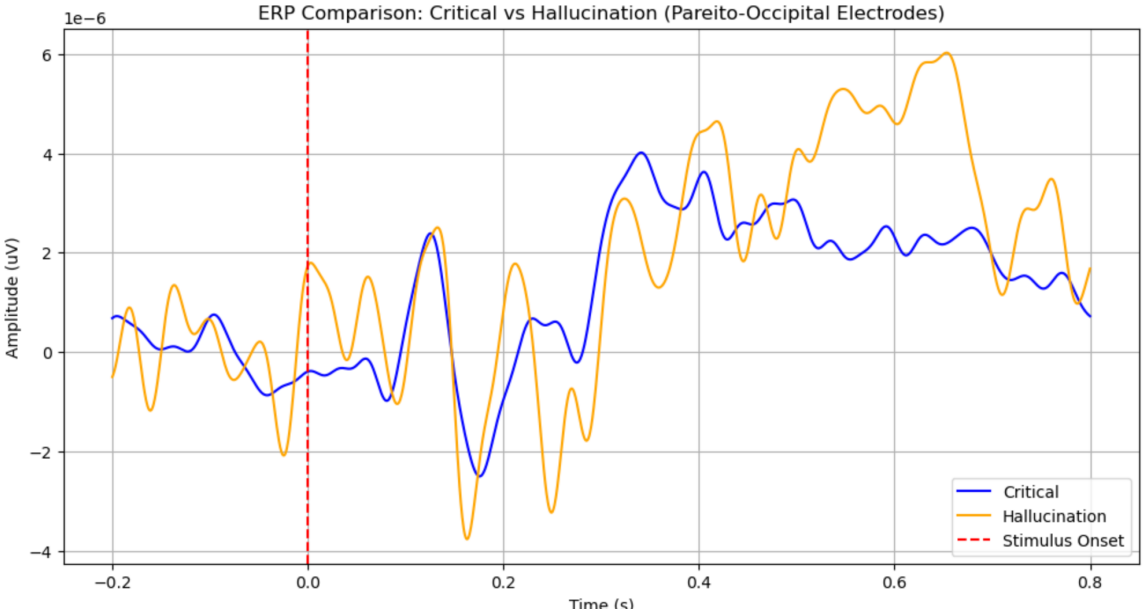

Figure 11. Grand Average ERP for the critical non-hallucination condition (13 participants) and the hallucination condition (12 participants) for parieto-occipital ROI.

Wilcoxon Signed-Rank Test results for mean ERP amplitudes revealed no statistically significant differences across 100 ms time windows in the Square Visibility Task for the parieto-occipital ROI. **Table 4.** provides the results, along with mean amplitudes and standard errors (SE) for each condition. While no significant differences were observed, the consistent large effect sizes across time window suggest that data stems from deviations caused by noise rather than meaningful neural activity. High variability in standard error (SE) across means in the hallucination condition suggests that the data lacks power, likely due to insufficient number of trials.

Table 4

Wilcoxon-Signed Rank Test Results for Mean ERP Amplitudes Across 100 ms Time Windows in the Square Visibility Task (Parieto-occipital ROI)

Time Window	Mean CR(µV)	SE CR (µV)	Mean HL (µV)	SE HL (µV)	Z-value	Effect Size	Corrected p*
0-100 ms	-0.401	0.121	0.585	0.124	-2.201	-0.899	0.248
100-200 ms	-0.163	0.166	-0.207	0.154	-0.105	-0.043	1.000
200-300 ms	0.356	0.260	-0.683	0.226	-2.201	-0.899	0.248

300-400 ms	3.280	0.360	2.434	0.616	-1.992	-0.813	0.248
400-500 ms	2.841	0.394	3.273	0.619	-1.572	-0.642	0.312
500-600 ms	2.238	0.377	4.726	0.660	-2.201	-0.899	0.248
600-700 ms	2.252	0.298	4.880	0.489	-2.201	-0.899	0.248
700-800 ms	1.401	0.223	2.190	0.287	-2.201	-0.899	0.248

Note. HL - Hallucination Condition, CR - Critical Condition, *Rank-Biseral Correlation, **Holm correction

Additionally, for hallucination condition, I calculated number of trials required to achieve good ERP data quality using signal-to-noise ratio (SNR) as a proxy. To estimate the number of trials required to achieve good ERP data, I used an SNR value of 3 as the desired threshold, serving as an indicator of good data quality. In the frontal electrodes the estimate trial number was 1767 with SNR of 0.41 and in the parieto-occipital electrodes estimate trial number was 53 with given SNR value of 2.37.

Discussion

In this study I explored whether there are hallucination related markers in event-related potentials (ERPs) recorded during the episodes of "normal" hallucinations (NH) induced in a behavioral experiment, as originally conducted by Aru et al. (2018). For this purpose, I also tested whether typical ERP components could be obtained with the equipment and analysis I used in visual (face) stimulus perception task. The experiment was conducted combining an exploratory EEG approach with replication of behavioral experiment to investigate neuronal correlates of NH. In my study I aimed to address the following main questions: (1) Does the experiment replicate the behavioral results reported in Aru et al. (2018)? (2) What are the effects of visibility ratings in critical trials and the effects of correctness of responses in the primary face orientation discrimination task on reaction times (RT)? (3) Can the generated ERPs and their details be reliably captured in individuals experiencing “normal” hallucinations, considering the statistical power calculated for the behavioral results in Aru et al. (2018)? (4) If captured, are there any observable differences in mean amplitudes when comparing the ERPs with experience of NH to the ERPs of trials without NH.

Firstly, to ensure that subjects followed the task and kept their focus and were not overloaded as a default procedure I analyzed the reaction times of the correct and incorrect responses in the primary face task. Significant difference in reaction times based on response accuracy was found, where participants who answered correctly had a faster average reaction time. By that it is possible to conclude that subjects followed the task with sufficient care and kept their focus (because this reaction time regularity is a standard finding in valid visual recognition experiments). In the present study, behavioral findings largely replicated earlier results (Powers et al., 2016, 2017; Aru & Bachmann, 2017; Aru et al., 2018; Vetik et al., 2020). Bachmann (2021), showing a high prevalence of NH in critical trials, significant correlations between visibility ratings and illusory perception scores and high rate of correct answers. The strong positive correlation between visibility ratings and illusory perception supports the idea that NH involves subjective experience rather than random guesses. Participants provided significantly higher visibility ratings for trials where the square was present compared to trials where it was absent. This shows that participants could distinguish between the presence and absence of the stimulus, even though they reported hallucinations in absent-stimulus trials. This suggests that illusory perception in critical trials was a genuine experience influenced by cognitive or neural mechanisms rather than indiscriminate or random responses. However, in future analogous studies it is advisable to test whether there could be a response bias effect in

producing NH clarity ratings due to the carry-over of the confidence acquired due to the clear perception of stimulus presence from stimulus present trials to the stimulus-absent trials. Participants also occasionally used higher visibility ratings (e.g., "3" or "4") even when the stimulus was absent, suggesting varying levels of perceptual clarity for the hallucinated object. This gradation of ratings indicates that normal hallucinations (NH) are not binary experiences but exist on a continuum of perceptual vividness. This observation aligns with findings from earlier research (Aru et al., 2018), which suggested that individual differences play some role in the occurrence and characteristics of NH. Specifically, Aru et al. (2018) reported a significant negative correlation between scores on the Autism Spectrum Quotient (AQ) and the frequency of NH. Participants with higher AQ scores—indicating traits associated with autism spectrum conditions—tended to experience NH less frequently.

For the second question, I also compared participant reaction times across visibility ratings given in critical trials with hallucinatory experience. Results showed that there was significant difference in reaction times across visibility ratings in NH trials. Specifically, participants in the "barely noticeable stimulus" condition had significantly slower reaction times compared to those in the "clear perception" condition and the "no perceptual awareness" condition. In the very weak hallucinatory experience trials, it took longer to produce the rating, which suggests that participants may have struggled to resolve the ambiguity of their perceptual experience, engaging more top-down processing to compensate for weak bottom-up input. One explanation for this finding could be that attention devoted to the primary face task might have influenced participants' ability to process the ambiguous stimulus. The observed moderate positive correlation between the illusory perception score and the number of correct answers in the primary face task suggests a potential relationship between task performance and hallucinatory experience. Although the correlation was not statistically significant, it indicates that participants who performed better on the primary task tended to experience more hallucinations during critical trials. This finding is strongly supported by the study conducted by Adelhöfer et al. (2019) demonstrating that perceptual ambiguity increases the engagement of inhibitory processes, as the brain works to suppress competing interpretations and arrive at a coherent perception. These inhibitory processes are modulated by stimulus-response transitions or decision-making processes, rather than purely stimulus-related mechanisms. This aligns with the current findings, where participants exhibited longer reaction times in ambiguous weak hallucinatory experience trials, reflecting the additional cognitive effort required to resolve uncertainty. Moreover, this observation is consistent with predictive coding frameworks where it is proposed that the brain allocates precision weighting to determine the

confidence assigned to prediction errors (O'Callaghan et. al, 2017). In the context of the present study, the longer reaction times in ambiguous trials could reflect increased reliance on top-down processing, where greater attention and cognitive resources are required to interpret uncertain stimuli and resolve perceptual ambiguity. Moreover, provided that a hallucinated percept was produced, the longer reaction time corresponds to the more decayed perceptual trace of the illusory experience, which relates longest reaction times to weakest NHs naturally. Further replication and additional studies on reaction times in ambiguously perceived stimuli are needed, as this could provide valuable information regarding the neural dynamics of top-down processes in forming hallucinatory experiences. The condition of a "barely noticeable stimulus" could potentially play a crucial role in top-down processes overriding bottom-up perception, resulting in longer reaction times.

Apart from the successful replication of the original behavioral study, the novelty of the current research lies in applying the EEG/ERP method to explore the neural underpinnings of non-hallucinatory (NH) experiences. The primary question addressed in this part of the study was: Can NH related ERP markers be reliably captured in individuals experiencing NH, considering the statistical power of the behavioral experiment by Aru et al. (2018)? The results underscore the critical importance of a sufficient number of trials for reliable data interpretation. This should motivate continuation of the current line of research.

In the EEG method validation analysis, reliable ERPs were obtained under the Face Orientation Task conditions with an adequate number of trials. This confirmed that the EEG recording setup was responsive to the stimulus presentation and capable of capturing typical ERP patterns in a well-controlled task. However, in the trials of primary interest—namely, those involving NH experiences—reliable ERPs could not be obtained due to an insufficient number of trials. This shortcoming led to a predominance of noise across all ERP wavelengths in NH conditions, as supported by low estimated signal-to-noise ratio (SNR) values. Visual inspection did not reveal distinct peaks, and the details of the generated ERPs could not be discerned.

As a result, it was not possible to address the final research question: whether observable differences in mean amplitudes exist when comparing ERPs from critical trials with NH to trials with no NH. For the conditions of interest, specifically the Square Visibility Task, statistical testing was deemed unnecessary because differences due to noice were visually apparent. Statistical tests revealed no significant differences between the conditions but did show large effect sizes. These large effect sizes, derived from rank-biserial correlation, are likely attributable to the sensitivity of non-parametric tests to noisy data, particularly when

values in one condition consistently prevail over those in the other. Indeed, visual inspection confirmed that the noisy ERP was more prominent in the hallucination condition than the non-hallucination condition. Overall, this study highlights the critical importance of ensuring an adequate number of trials when designing ERP experiments where very subtle perceptual experiences are studied. Reliable data interpretation depends on robust SNR values and the ability to detect distinct ERP peaks, particularly in conditions of interest. Future research should prioritize trial sufficiency and methodological rigor to effectively bridge behaviorally observable results with brain data recording methods, such as EEG, in the context of "normal hallucinations."

Limitations

The primary limitation of the current study was insufficient statistical power to reliably capture event-related potentials (ERPs). The low number of trials in the conditions of interest, particularly for hallucination trials, resulted in high noise levels across ERP wavelengths and low signal-to-noise ratio (SNR) values. This lack of power limited the study's ability to detect distinct ERP components and conduct further analysis. The low statistical power arose not only from the number of participants but also from the structure and duration of the behavioral experiment itself. Specifically, for each participant, the experiment lasted up to 15 minutes, which is relatively short compared to typical ERP studies that often span up to hours. On the other hand, increasing the number of trials without actual stimulus would increase probability that participants discover the design and report absence of stimulus even if they experienced hallucination.

To address the limitations, future studies should increase statistical power by recruiting more participants, extending the experiment duration, and including sufficient breaks between blocks to reduce participant fatigue. Moreover, it is critical to conduct targeted behavioral studies to calculate the highest possible number of critical trials while maintaining a prevalence of hallucinatory experiences above 50%. This study included only four critical trials per participant, which, even with a larger sample size, may still be insufficient to achieve reliable ERP data. Combining longer experiment durations with an increased number of critical trials – optimized to sustain hallucination prevalence – will be key to effectively raising statistical power.

In addition, the methodology of artifact rejection presented another limitation. In this study, Independent Component Analysis (ICA) was applied to continuous raw data for artifact removal (e.g., eyeblinks and muscle noise) prior to epoching. While this approach effectively

removes global artifacts, it risks removing clean signal components, potentially resulting in lower Signal-to-noice-ratio (SNR). In event-related studies, some researchers recommend applying ICA after epoching to isolate and remove artifacts more effectively while preserving neural signals. Future studies should explore this alternative approach, particularly when working with limited datasets.

Electrode connectivity and impedance quality also presented a challenge for this study. Despite efforts to maintain optimal electrode connectivity, some frontal electrodes displayed lower impedance quality, rated as “poor.” This issue may have been caused by the age and wear of the EEG cap, including electrode oxidation. This was reflected in very low SNR values for frontal regions. Future research should prioritize maintaining optimal electrode impedance, especially in frontal regions, and consider upgrading equipment to ensure high-quality recordings.

Finally, I calculated the power based on SNR values to provide a framework for future research. The analysis revealed significant differences in the estimated trial numbers between electrode regions. Considering the relatively better connectivity of the parieto-occipital electrodes and their higher voltage readings, the power analysis indicated a minimum of 53 trials for achieving reliable ERPs. While this estimate appears more realistic compared to the frontal electrode requirements, it may still be questionable due to other limitations in the experimental setup, such as overall noise levels and trial variability. Therefore, it is advised to aim for at least 100 trials in future studies while maintaining a focus on improving electrode connectivity and refining experimental design to enhance data quality and reliability.

Conclusion

This study explored the putative neuronal correlates of “normal” hallucinations (NH) using event-related potentials (ERPs) during a dual-task paradigm. Behavioral results successfully replicated earlier findings, showing the prevalence of NH and their correlation with subjective visibility ratings and task accuracy. Reaction times in ambiguous trials suggested increased cognitive effort, supporting the role of top-down processes in resolving perceptual uncertainty.

However, insufficient trial numbers in hallucination conditions led to high noise levels and low signal-to-noise ratios, limiting the ability to reliably capture ERPs. While ERPs were successfully recorded in a control task, the NH condition requires more robust designs for future studies. To enhance reliability, future research should increase trial numbers, extend

experiment duration, and optimize preprocessing methods. These improvements will enable more accurate exploration of the neural mechanisms underlying NH and their relevance to cognitive and perceptual processes.

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Appendix 1. Participant informed consent form

AJU BIOELEKTRILISTE POTENTSIAALIDE VÕNGETE UURIMINE VISUAALSE TAJU TÕESUSE KONTEKSTIS: SÜNDMUSPÕHISTE POTENTSIAALIDE UURING

Uuritava informeerimise ja teadliku nõusoleku vorm

Uuring: Aju bioelektriliste potentsiaalide võngete uurimine visuaalse taju tõesuse kontekstis: Sündmuspõhiste potentsiaalide uuring

Kutsume Teid osalema Tartu Ülikooli (TÜ) psühholoogia uuringus "Aju bioelektriliste potentsiaalide võngete uurimine visuaalse taju tõesuse kontekstis: Sündmuspõhiste potentsiaalide uuring", mille eesmärk on paremini mõista, kuidas aju aktiivsus on seotud visuaalse stiimulite tõepärase tajumisega.

Uuringus osalemine on vabatahtlik. Teil on õigus uuringus osalemisest loobuda ja/või katse igal hetkel katkestada. Uuringus kogutud andmeid ei avaldata isikut tuvastada võimaldaval kujul väljaspool uurijate ringi. Andmed säilitatakse ja kasutatakse anonüümsel kujul Tartu Ülikooli One Drive pilveteenuses. Katse käigus kogutud andmeid ning informeeritud nõusoleku vorme säilitatakse kuni 1 juuni 2025. Informeeritud nõusoleku vorme hoitakse TÜ eksperimentaalpsühholoogia laboris aadressil Ravila 14a. Uurimistöös kogutud andmete vastutav töötleja on Tartu Ülikooli psühholoogia instituut.

Katse käigus esitatakse Teile arvutiekraanil visuaalseid stiimuleid kahes eraldi katseseerias, igaühes 120 trialit. Iga stiimuli puhul palutakse Teil täita katse-eelses instruktsioonis kirjeldatud mentaalsed ülesanded, mille eesmärk on hinnata, kuidas Teie taju vastab tegelikkusele. Katsete vahel on paus, mis võimaldab Teil puhata ja valmistuda järgnevaks seeriaks. Katseseeriate ajal mõõdetakse Teie vastuste õigsust ja aju bioelektrilist aktiivsust elektroentsefalograafia (EEG) abil.

Enne katsega alustamist asetatakse Teile pähe elektroodidega EEG müts. Kasutatav EEG aparatuur (Nexstim Ltd., Helsinki, Finland) on ohutu ning vastab rahvusvahelistele nõuetele. On oluline märkida, et EEG kui elektriline aparatuur võib ohustada katseisikut juhul kui tekib rikkest või kasutusveast põhjustatud elektrivoolu kahjustus. Seetõttu viiakse katsed läbi (i) eelnevalt põhjalikult instrueeritud eksperimentaatori poolt, (ii) alles aparatuuri korrasoleku eelkontrolli järel. Mõnikord võib EEG mütsi paigaldamine olla ebamugav. Sellisel juhul tuleb sellest teada anda, misjärel eksperimentaator tagab ebamugavuse puudumise. Kui ebamugavusprobleemi ei saada kõrvaldada, katkestatakse EEG sessioon. EEG mütsi paigaldamisel kasutatakse antiallergeenset soolageeli, mis määrib juukseid. Katseisikutel on võimalus pärast katse lõpetamist pead pesta.

NB! Palun varuge kannatust, kuna EEG mütsi paigaldamine võib võtta kuni kolmveerand tundi aega.

Uuring viiakse läbi Tartu Ülikooli psühholoogia instituudi eksperementaalpsühholoogia laboris Chemicumi majas, aadressil Ravila 14a, kabinett 2004. Katse läbiviija tuleb Teile kokku lepitud ajal vastu Chemicumi fuajeesse. Katse kestab pärast EEG mütsi paigaldamist pausideta

kokku umbes 20 minutit (tegelik kestus sõltub iga osaleja vastuse andmise kiirusest ja osaleja poolt vastavalt vajadusele võetud pausidest).

Käesolevas uuringus osalemisel kinnitan järgnevat (märgi kõik sobivad):
o olen täisealine (18-aastane või vanem);
o olen paremakäeline;
o olen normaalse või normaalseks korrigeeritud nägemisega (vajadusel kannan prille või kontaktläätsesid);
o olen hetkel hea tervise juures, sh ei ole mul diagnoositud migreeni, epilepsiat, krampe, insulti, ajuverejooksu, kõrgvererõhutõbe, südamerikkeid ega psüühilisi häireid; o mul ei ole metallist implantaate peas ega breketeid
o ma ei kasuta stimulaatorit, kuuldeaparaati, implantaati või ravipumpa;
o ma ei ole tarvitanud narkootilisi ega psühhotroopseid aineid, seahulgas kofeiini sisaldavaid jooke (kohvi, Coca-Cola jm) vähemalt 6 tundi enne katsesse asumist;

Kui mõni eelnevatest on valimata, ei ole kahjuks võimalik uuringus osaleda.

Kui Teil on täiendavaid küsimusi, võtke ühendust vastutava uurijaga (e-post: talis.bachmann@ut.ee).

Kui Teil tekib küsimusi uuringus osaleja õiguste kohta, siis pöörduge palun Tartu Ülikooli inimuuringute eetika komitee poole e-posti aadressil eetikakomitee@ut.ee; telefonil 737 6215. Kaebustega isikuandmete töötlemise osas palume pöörduda Tartu Ülikooli andmekaitsespetsialisti poole e-posti aadressil andmekaitse@ut.ee.

Katse läbiviija: _____ Kuupäev: _____

Allkiri:_____

Mind, _____, on informeeritud ülalmainitud uuringust ja ma olen teadlik läbiviidava uurimistöö eesmärgist, uuringu metoodikast, vastusnäidustustest ning võimalikest kahjuohtudest.

Annan nõusoleku oma isikuandmete töötlemiseks

Allkiri: _____ Kuupäev: _____

Kinnitan oma nõusolekut selles uuringus osalemiseks allkirjaga.

Allkiri: _____ Kuupäev: _____

Olen huvitatud kutsete saamisest analoogsetes psühholoogilistes uuringutes osalemiseks. Selleks luban endaga ühendust võtta aadressil: _____

Appendix 2. Experiment protocol

VISUAALSE TAJU TÄPSUSE KATSE PROTOKOLL

A: Saame tuttavaks, minu nimi on Anton ning ma olen selle uuringu teostaja. See uuring viiakse läbi uurimistöö aine raames. Olete üks nendest, kelle katsetulemused on väga väärtuslikud minu tööks. Katsetulemused säilitatakse anonüümselt ja jäävad konfidentsiaalseks; tulemusi ei ole kolmandatel isikutel võimalik Teie isikuga seostada.

A: Uuringu peamiseks eesmärgiks on paremini mõista, kuidas aju aktiivsus on seotud visuaalsete stiimulite tõepärase tajumisega. Katse ajal mõõdetakse Teie vastuste täpsust ja aju bioelektrilist aktiivsust elektroentsefalograafia (EEG) abil. Kasutatav EEG aparatuur ei kujuta osalejatele ohtu ning vastab rahvusvahelistele nõuetele.

A: Meie uuringu põhimõtteline ülesehitus on järgmine:

1. Kõigepealt saate tutvuda Katseisiku Nõusoleku Vormiga, mis tuleb läbi lugeda ning allkirjastada juhul kui olete nõus katses osalema.
2. Seejärel alustame prepareerimist, mis tähendab pea mõõtmist, et valida sobiva suurusega EEG müts ® mütsi paigaldamine ® geeli lisamine elektroodidesse, et suurendada elektroodide juhtivust.
3. Esitan instruktsiooni sellest, milline on katse üleseitus ja mida Teil tuleb katses teha.
4. Katse läbimine.

.....
.....

Pärast vormi allkirjastamist:

Üks koopia jääb Teile ning teine jääb meile ning seda säilitatakse kuni järgmise aasta juunini kõrvalistele isikutele mitte juurdepääsetavalt.

A: Kordan veel, et osalemine on täiesti vabatahtlik ja võite igal ajal katsest loobuda.

.....
.....

Pärast mütsi paigaldamist:

A: Mõnikord võib EEG mütsi paigaldamine olla ebamugav. Sellisel juhul tuleb sellest mulle teada anda ning leiame lahenduse. Kui ebamugavusprobleemi ei saada kõrvaldada, katkestatakse EEG sessioon. EEG mütsi paigaldamisel kasutatakse antiallergeenset soolageeli, mis teeb juuksed geeliga kokku üksikute elektroodide juures. Sul on võimalus pärast katse lõpetamist pead pesta privaatses dušširuumis, kuhu ma juhatan pärast katse lõpetamist.

.....
.....

Instrueerimine (juhis eksperimentaatorile)

Algtingimused:

- - Arvutil on avatud VisualEgg dialoogiaken koos parametritega
- - EEG paigaldamine on edukalt lõpetatud
- - Katseisik istub ca 80 cm kaugusel ekraanist
- - Näidan ki-le lehte, kus on kujutatud 4 erinevat näokujutist ja tutvustan neid kui katsete

  põhistiimulite näiteid

1. Esimeses proovikatses:

Ekraanil sähvatab korraga keskkohast paremal ja vasakul pool nägu. Nägusid esitatakse neljas erinevas kombinatsionis: mõlemad näod püstiselt, mõlemad näod ümber pööratult, vasak nägu püstiselt ja parem ümber pööratult ning vasak nägu ümber pööratult ja parem püstiselt.

Sinu ülesanne on võimalikult kiiresti vastata, kas näod olid mõlemad samapidi (st mõlemad õigetpidi või mõlemad ümber pööratult) või suunalt erinevad (üks õigetpidi, teine ümber pööratult). Selliseid üksikkatsetusi on korduvalt.

Vastused saad anda klahvidega: sama (S), erinev (K). (Näitan klahve)

Et edukalt ülesannet lahendada, tuleb hoida pilk kogu aeg monitori keskel asuval fiksatsiooniristil, suunates tähelepanu korraga kahel pool asuvatele nägudele.
Lisaks sähvatab ekraani keskel ruuduke, millele praegu tähelepanu pöörama ei pea.

Harjutusblokiga alustamiseks vajuta tühikut A: - Jõudsite teise proovikatseni!

2. Teises proovikatses:

- Näidan katseisikule lehte, kus on kujutatud ruudu kontrasti varieerumine.

Katses esitatav jääb samaks, kuid nüüd tuleb tähelepanelikult **jälgida ekraani keskel sähvatavat ruutu**. Ruudu kontrast varieerub, seega mõnikord on seda selgesti näha, teinekord vaevuaimatavalt. Sinu ülesanne on anda hinnang neljapallisel skaalal, kui selgesti ruute tajusid: (ei kogenud ruutu, kogesin ruutu vaevuaimatavalt, kogesin ruutu peaaegu selgesti, kogesin ruutu selgesti). Sellele küsimusele pole õiget vastust. Oluline on edasi anda oma subjektiivne tajukogemuse selgus. Vastuseid saad anda klahvidega A, D, J, L, mis tähendavad vastavalt ruudu mittekogemist, vaevuaimatavat kogemist, peaaegu selget kogemist ja selget kogemist.

A: - Nüüd olete jõudnud põhikatseni.
- Dubleerin ekraanil kirjutatavat, rõhutades olulised kohad

3. Põhikatses:

Kõik on sama nagu harjutusblokkides.

Enamikel kordadel esitatakse küsimus nägude kohta. kuid mõnikord esitatakseküsimus ruudu selguse kohta.

Hoia pilku keskel ja püüa olla tähelepanelik. Varasemad uurimused on näidanud, et sedalaadi ülesande täitmisel on tulemused täpsemad, kui katseisik suudab hoida stiimulite sähvatamise ajal oma pilku keskel asetseval fiksatsiooniristil ja ei püüa vaadate ühele või teisele poole.

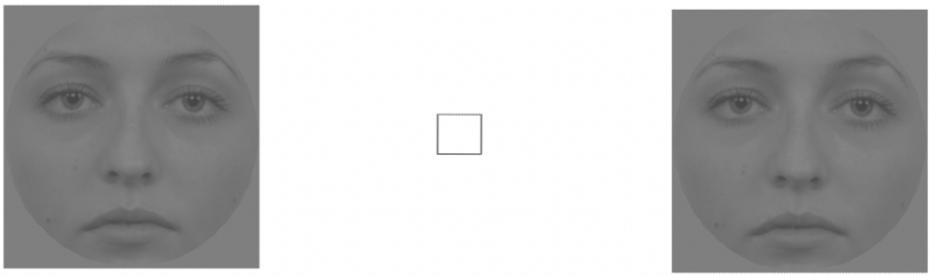
Katses on 2 blokki, mille vahepeal saad silmi puhata.

.....
.....

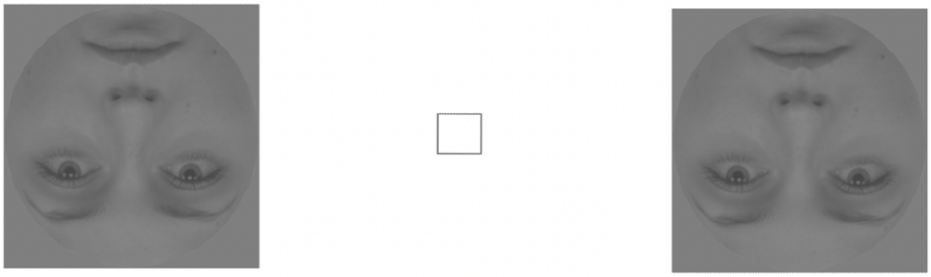
A: Katse on lõppenud! Võid jagada oma mõtteid või esitada küsimusi. Võtan elektroodmütsi maha ning viin KI dušširuumi kui ta soovib.

Appendix 3. Participant guidance sheet for completing the task.

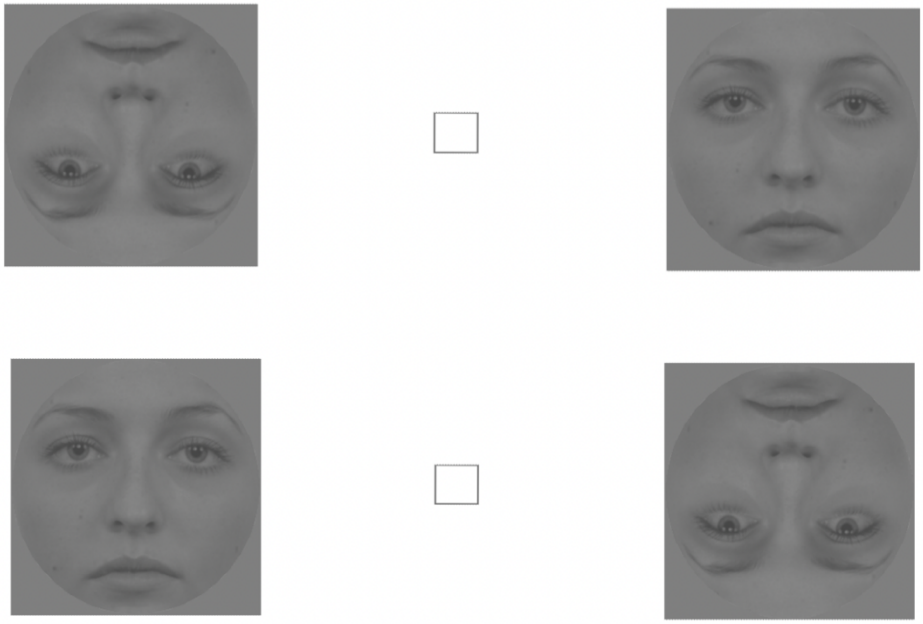
Näod on samapidi (mõlemad õigetpidi)



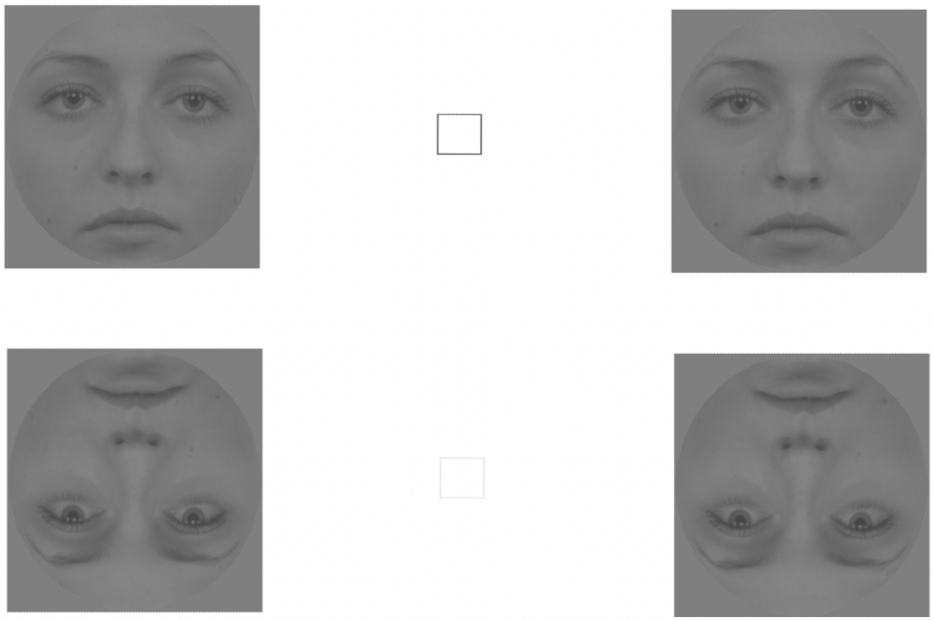
Näod on samapidi (mõlemad tagurpidi e ümber pööratult)



Näod on pööratud erinevalt (parempoolne õigetpidi ning vasakpoolne tagurpidi e ümber



Mõnikord on ruutu selgesti näha, teinekord vaevuaimatavalt



Consent for publication

I hereby confirm that I have correctly referenced all written scientific papers, sentences, thoughts, ideas or texts created by other authors used in my work. I agree to the publication of my work in the University of Tartu digital archive DSpace.

Anton Kislitsõn