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Dynamics of oculomotor patterns during prolonged visual processing

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Abstract This study examines the dynamics of behavioral and physiological responses during prolonged engagement with an ambiguous visual stimulus. Over the course of the experiment, which involved the presentation of the Necker cube, participants demonstrated a reduction in error rate and reaction time, indicating a learning effect despite increasing fatigue levels, as revealed by subjective assessments. Analysis of eye-tracking data showed that fixation duration significantly correlated with error rate, suggesting shifts in cognitive processing strategies throughout the experiment. Additionally, pupil size was found to be larger during incorrect interpretations, which may indicate the predominance of an insight-based strategy in error-prone trials. These findings provide further insight into the adaptive mechanisms of perceptual decision-making under conditions of ambiguity.

1 Introduction

The processing of visual information is essential for human perception, enabling effective interaction with the environment. A particularly important aspect is the interpretation of ambiguous stimuli, which provides insight into decision-making mechanisms and cognitive strategies [1–3]. Analysis of oculomotor activity during perceptual decision-making opens up opportunities to understand the cognitive processes that underlie the perception and processing of visual information [4, 5].

Eye movements during visual perception include fixations, saccades, and pupil size changes, each reflecting various aspects of cognitive processing [6–8]. Fixations indicate attention distribution and information extraction, saccades represent active exploration strategies, and changes in pupil size can reflect cognitive load and decision-making processes [9–11]. The Necker cube is one of the classic tasks for studying the perception of ambiguous visual stimuli.

Previous studies have shown that eye movement patterns can reveal various cognitive strategies across diverse tasks [1, 9]. However, the evolution of these patterns under prolonged exposure to ambiguous stimuli and their relationship with perceptual learning and fatigue effects remain underexplored. Understanding these relationships could provide valuable insights into the mechanisms of perceptual decision-making and adaptive cognitive strategies.

Thus, the study of oculomotor activity represents a promising direction, especially in the context of cognitive function research. In this regard, the aim of this work is to investigate the characteristics of eye movements and their relationships with the efficiency of processing ambiguous visual stimuli, including the evolution of activity patterns under prolonged exposure to stimuli.

This study focuses on examining oculomotor activity patterns during the processing of ambiguous visual stimuli using eye-tracking methodology. The research emphasizes the relationships between fixation duration, pupil size, and other eye movement characteristics with the efficiency of perception and their changes over time. The results demonstrate various oculomotor behavior patterns associated with different perceptual outcomes and learning effects.

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2 Materials and methods

2.1 Experimental procedure

The experimental procedure was based on a study on perceptual bias during the interpretation of the Necker cube [12]. The Necker cube, a classical bistable image that can be perceived as oriented in two different directions, serves as an effective model for studying the processing of ambiguous visual information [13]. Manipulating the level of ambiguity by adjusting the intensity of certain edges allows for systematic investigation of how perceptual uncertainty influences visual processing strategies and decision-making. The experiment used images of the Necker cube with varying degrees of ambiguity controlled by the parameter B (intensity of the central edges). The values of B ranged from [0, 1], where $B = 0$ corresponded to a left-oriented cube, $B = 1$ to a right-oriented cube, and $B = 0.5$ to a maximally ambiguous cube. The stimulus set included eight Necker cube images, categorized into low ambiguity ($L = 0.15$, 0.25, 0.75, 0.85), which were easily interpreted, and high ambiguity ($H = 0.40$, 0.45, 0.55, 0.60), which required greater effort for interpretation.

The experiment consisted of 480 trials. Each trial included the following sequence: a fixation point (0.5–1 s), a Necker cube (1−1.5 s), and an abstract noise image (3–5 s). The stimuli were presented on a 24-inch LCD monitor (1920×1080 pixels, 60 Hz) at a distance of 70–80 cm. The size of the cube image was 14.2 cm (viewing angle ∼0.25 rad). The task required participants to determine the cube's orientation (left/right) by pressing the corresponding button.

To assess fatigue, the VAS (visual analog scale) [14] and MFI (multidimensional fatigue inventory) [15] tests were conducted before and after the experiment.

2.2 Data acquisition and preprocessing

Oculographic data were recorded throughout the experiment using the EyeLink 1000 Plus system. Gaze coordinates and pupil size were registered for both eyes. Preprocessing included the removal of blink artifacts and periods of signal loss.

For analysis, two time-of-interest (TOI) periods were defined: the presentation of the Necker cube and the display of the noise image. Fixations and saccades were identified using an algorithm based on sliding dual-coordinate window approximation with a parametric saccade model [16, 17]. The thresholds for saccade detection were set as follows: minimum duration − 10 ms, velocity − 30°/s, acceleration − 8000°/s^2 [18, 19].

Prior to analyzing the effect of pupil size, preprocessing was performed to exclude trials where blinks were detected, as they could affect pupil size. To minimize individual differences among participants, pupil size normalization using z-score was applied. This method was chosen because it effectively accounts for inter-individual variability while preserving within-subject dynamics, making it particularly useful in studies involving prolonged tasks [20, 21].

All statistical analyses were performed using the Python programming language, specifically utilizing the NumPy, SciPy, and statsmodels libraries for statistical computations, as well as pingouin for advanced statistical tests. To assess changes in behavioral and physiological parameters over time, repeated measures analysis of variance (RM ANOVA) was applied. Post hoc comparisons were conducted using the Conover test with Bonferroni correction to control for multiple comparisons. The Wilcoxon signed-rank test was used to analyze non-normally distributed paired data, while the Friedman test was employed for repeated non-parametric comparisons. Correlations between continuous variables were assessed using Spearman's rank correlation coefficient, while repeated measures correlations were computed to examine within-subject relationships between fixation duration and task performance. Effect sizes were reported using Cohen's d for parametric tests and rank-biserial correlation for non-parametric tests. Statistical significance was set at $\alpha = 0.05$. All reported p values were adjusted for multiple comparisons where applicable.

The experimental data were divided into four blocks of 120 trials each to analyze the dynamics of oculomotor metrics. For each block, the average values of fixation duration, pupil size, and error rates in cube orientation interpretation were calculated.

2.3 Participants

The study involved 26 healthy volunteers (aged 18–26) with normal or corrected-to-normal vision. There were 20 boys and 6 girls. None of the participants had a diagnosed central nervous system disorder. All experiments were conducted in the first half of the day.

The study was conducted in accordance with the Declaration of Helsinki and approved by the local ethics committee. Prior to the experiment, participants were informed about the study's objectives and methods. Each participant provided written informed consent to participate in the study.

3 Results

To understand the features of oculomotor activity during the processing of ambiguous visual information, it is essential to first evaluate the effectiveness of task performance. For this purpose, an analysis of behavioral characteristics—error rate and reaction time—was conducted under conditions of varying stimulus ambiguity and at different stages of the experiment. Figure 1 shows the dependence of error rate (Error) (A) and reaction time (Reaction time) (B) on the experimental block for two levels of ambiguity (complexity): high (H) and low (L). Mean values and standard deviations are indicated.

Repeated measures ANOVA revealed significant main effects of the factors block and complexity for both behavioral characteristics. For error rate, a significant decrease was observed across blocks (see Fig. 1A). Statistically significant differences were found between blocks 1 and 3 ($p = 0.008$, $t = 3.278$, Cohen's $d = 0.317$) and blocks 1 and 4 ($p = 6.556e - 5$, $t = 4.729$, Cohen's $d = 0.457$), with effect sizes increasing from block to block.

The analysis of reaction time showed a reduction over the course of the experiment (see Fig. 1B), with the most pronounced differences observed between the first block and subsequent blocks: 1–2 ($p = 1.476e - 6$, $t = 5.599$, Cohen's $d = 0.821$), 1–3 ($p = 4.729e - 9$, $t = 7.037$, Cohen's $d = 1.032$), 1-4 ($p = 3.504e - 10$, $t = 7.689$, Cohen's $d = 1.128$). It is important to note that both error rate and reaction time were significantly higher for stimuli with high ambiguity (H) compared to those with low ambiguity (L) throughout the experiment.

In prolonged cognitive studies, task performance can vary significantly due to participant fatigue. To assess this factor, the MFI was utilized in this study, enabling the evaluation of various aspects of fatigue.

The analysis of results revealed significant changes across all scales by the end of the experiment (Fig. 2A). The most pronounced increases were observed on the scales of general fatigue, physical fatigue, and mental fatigue. Less pronounced, but statistically significant changes were recorded on the scales of reduced activity and decreased motivation.

A detailed analysis of the general fatigue scale (Fig. 2B) revealed a significant increase in values across all study participants (Wilcoxon signed-rank test: $p = 1.644e - 5$, $z = -4.305$, rank-biserial correlation $= -0.966$). The distribution chart shows a shift in the median and quartiles towards higher values at the end of the experiment compared to the baseline. The interquartile range also increased by the end of the experiment, indicating greater variability in individual fatigue levels.

These results demonstrate a substantial increase in subjective fatigue by the end of the experiment, which is particularly noteworthy in the context of the previously described improvement in behavioral performance and suggests the presence of compensatory mechanisms [22]. This raises the question of whether objective physiological markers also reflect the observed increase in fatigue.

Since blink duration is an involuntary physiological parameter reflecting the level of objective fatigue, an analysis of this metric was conducted throughout the experiment. The Friedman test revealed significant changes in blink duration over the course of the experiment ($p = 3.222e-6$). Post hoc analysis using the Conover test demonstrated a substantial increase in blink duration from the first to subsequent blocks (Fig. 3A).

Spearman's correlation analysis identified a statistically significant relationship between blink duration in the final block and the subjective fatigue level reported after the experiment ($\rho = 0.564$, Fig. 3B). This indicates consistency between objective and subjective measures of fatigue. The presented results confirm the development of fatigue during the experiment, which is particularly noteworthy in the context of the observed improvement in behavioral performance.

A detailed analysis of the dynamics of eye movement characteristics under various experimental conditions was conducted. Rapid eye movements, including peak velocity, duration, amplitude, and frequency, as well as fixation positions and durations, were examined. For each stimulus presented during the task, TOI intervals were identified, specifically the periods corresponding to the presentation of the Necker cube and the preceding noise. Eye movement characteristics were calculated for each of these intervals and their dynamics throughout

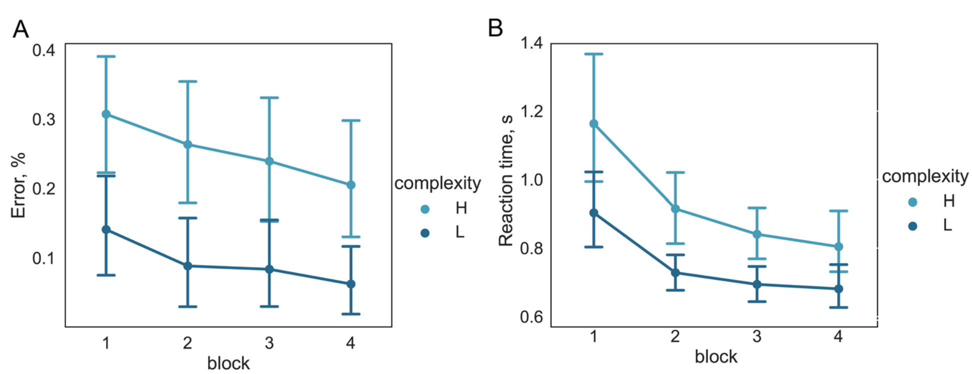


Fig. 1 Dependence of the percentage of error rate (Error) (**A**) and response time (Reaction time) (**B**) on the experimental block for two levels of ambiguity (complexity): high (H) and low (L). Mean values and standard deviations are shown

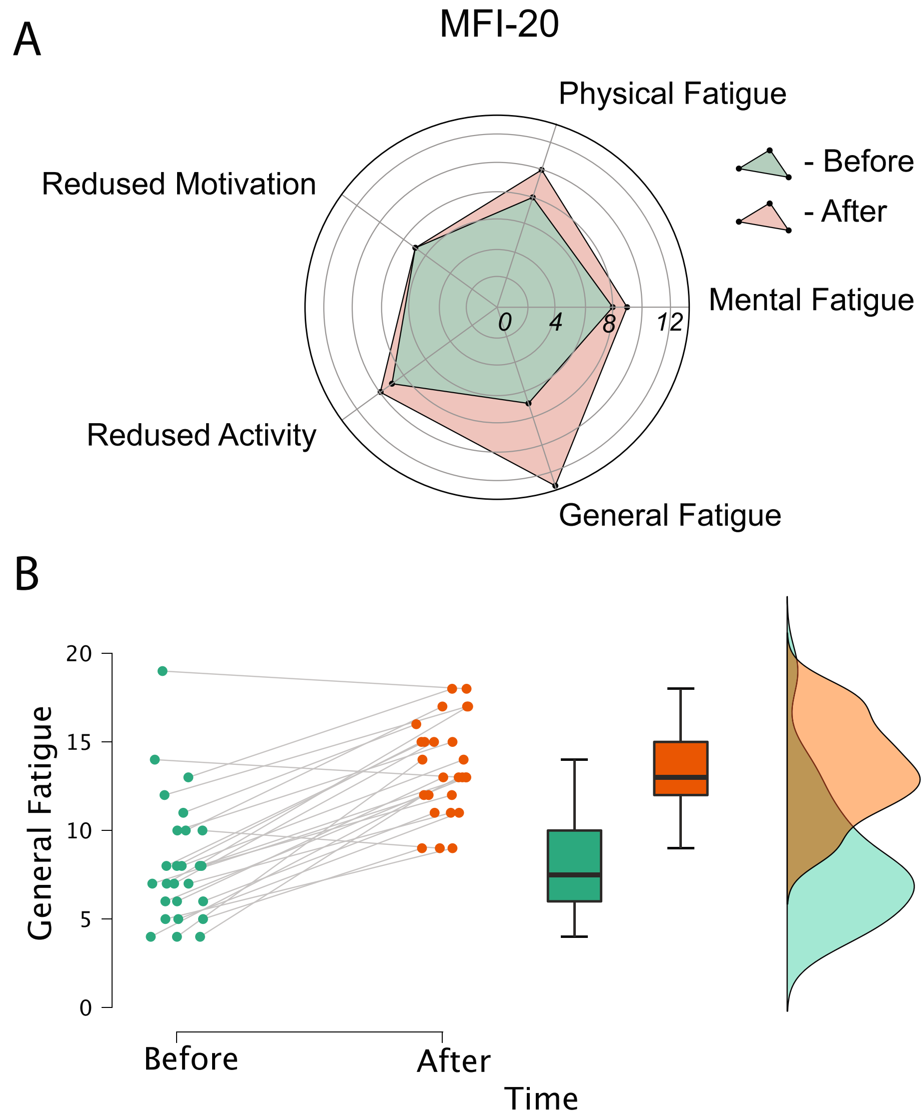


Fig. 2 MFI test results at the beginning and the end of the study for five scales (**A**); distribution of "general fatigue" scale values in the participant group at the beginning and the end of the study (**B**)

the experiment were analyzed. RM ANOVA revealed statistically significant changes in fixation duration for the factors experimental block (Block) and trial phase (Part of trial, cube presentation and noise presentation). Fixation duration during noise presentation was found to differ significantly from cube presentation ($p = 5.144e{-}5$, $F = 24.167$). Additionally, an interaction effect was observed between the factors block and trial phase ($p = 0.003$, $F = 6.150$). Post hoc analysis showed that the difference in fixation duration between cube and noise phases decreases over the course of the experiment. In the first block, fixation duration during cube presentation was significantly shorter than during noise presentation ($p = 1.681e - 5$, $t = -5.829$, and Cohen's $d = -0.766$). In the second ($p = 5.127e - 4$, $t = -4.794$, Cohen's $d = -0.630$) and third ($p = 0.01$, $t = -3.794$, Cohen's $d = -0.498$) blocks, the statistical difference persisted, but the effect size decreased block by block. In the fourth block, no statistically significant differences between cube and noise phases were observed. The dependence of fixation duration in different areas of interest and experiment blocks is presented in Fig. 3C, D.

The obtained results suggest that changes in the participant's state occur during the moments preceding the presentation of the cube. To analyze the relationship between these changes and task performance, a correlation analysis was conducted between fixation duration during the noise phase and the error rate. It was found that changes in fixation duration significantly correlate with the error rate ($r = 0.31$, $p = 0.007$, see Fig. 4).

An analysis of behavioral characteristics revealed that the number of errors significantly increases under conditions of high ambiguity in visual stimuli. To further explore this effect, differences in gaze fixation characteristics were examined during correct and incorrect interpretations of the Necker cube. It was found that incorrect interpretations were associated with an increase in pupil size compared to correct responses ($p = 0.009$, $z = 2.570$, rank-biserial correlation = 0.588). The results are presented in Fig. 5.

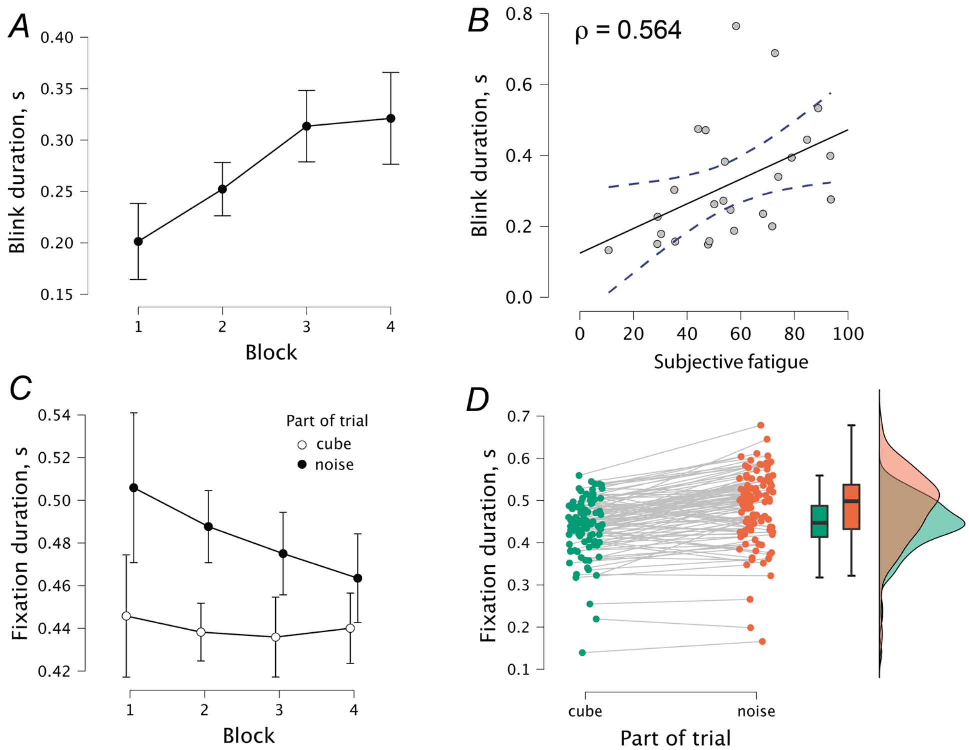
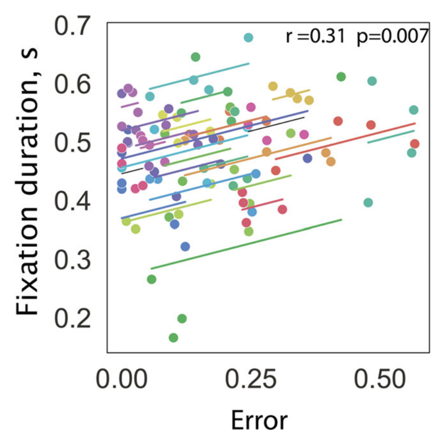


Fig. 3 (**A**) Dependence of the average blink duration on the experimental stage (block). The "whiskers" on the graph represent the 95% confidence interval. (**B**) Dependence of the average blink duration in the 4th block on the subjective fatigue score (VAS test) obtained immediately after the end of the 4th block. (**C**) Dependence of the average fixation duration at the moment of noise presentation (black dots) and cube presentation (white dots) on the experimental stage (block). The error bars on the graph represent the 95% confidence interval. (**D**) Results of comparing the average fixation duration between the moments of cube presentation (green dots) and noise presentation (orange dots) for each participant–block pair

Fig. 4 Repeated-measures correlations between fixation duration during the noise stage and the error rate. The top-right corner indicates the correlation coefficient ($r = 0.31$) and the statistical significance level ($p = 0.007$). Different colors represent individual participants, with each line illustrating the correlation for a specific participant



4 Discussion

This study examined the behavioral and physiological correlates of performing a task involving the processing of ambiguous visual information using the Necker cube. The main objective of the research was to identify the relationships between gaze fixation characteristics, sensory processing errors, and reaction time. The experimental paradigm involved presenting stimuli with varying degrees of ambiguity, while eye-tracking parameters, including fixation duration and pupil size, were recorded.

Our results showed that error rates and reaction times decreased significantly from the beginning to the end of the experiment, indicating a learning effect on participants. Despite this, subjective tests revealed an increase

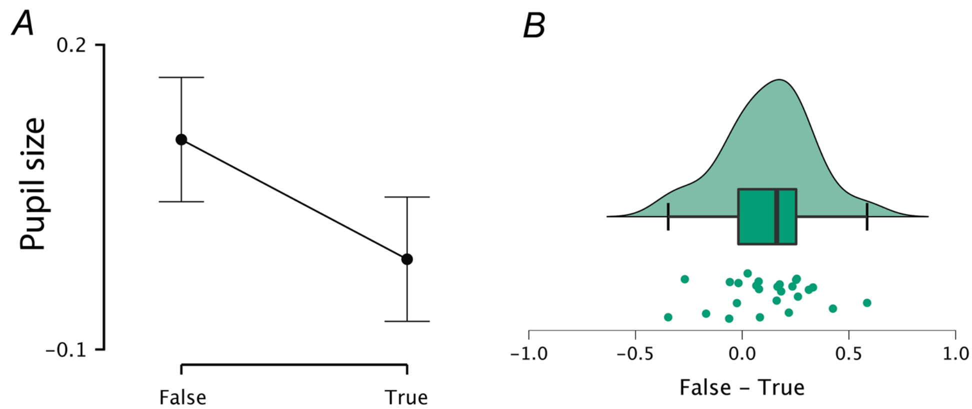


Fig. 5 (**A**) Dependence of the average pupil size during perception of the stimulus information (Necker cube) on errors in sensory perception versus correct responses, and in panel (**B**) the corresponding distribution of differences. The error bars on the graph represent the 95% confidence interval

in participant fatigue during the experiment. Thus, the improvement in performance may be attributed to the development of information-processing strategies that compensate for the effects of fatigue [22]. The study suggests that compensatory mechanisms allow participants to maintain cognitive performance despite increasing fatigue by reallocating mental resources. Specifically, the frontoparietal network adapts to the cognitive load by increasing connectivity and efficiency for high-complexity tasks while exhibiting a decline in performance for low-complexity tasks, indicating a selective engagement of compensatory effort depending on task demands.

Additionally, the analysis of gaze-tracking parameters revealed that under conditions of high stimulus ambiguity, longer fixations and increased pupil size were observed, potentially indicating the recruitment of additional cognitive resources for processing complex information. This aligns with existing findings on cognitive strategies, such as "insight", which is accompanied by pupil dilation prior to decision-making [23]. The results of this study also confirm the importance of adapting information processing strategies under conditions of ambiguity. The identified differences in fixation duration and pupil size suggest the presence of two primary approaches to interpreting the Necker cube: analytical and intuitive. The analytical approach involves a detailed analysis of edge intensities, whereas the intuitive approach is associated with perceiving the cube as a three-dimensional object, which may lead to a higher error rate.

According to the study [24], fixation duration can reflect the direction of cognition, whether internal or external. In the context of this study, the results may indicate a shift in participants' attention from internal to external focus over the course of the experiment, as evidenced by changes in fixation duration and accompanied by a reduction in interpretation errors.

The obtained data are consistent with existing studies showing that visual information processing involves both ventral and dorsal pathways. The ventral pathway is responsible for object recognition, while the dorsal pathway is associated with attention control and visuomotor coordination [25]. Moreover, changes in fixation parameters and pupil response may reflect the dynamic reorganization of cognitive networks during adaptation to new tasks. Thus, our results emphasize the importance of studying biometric data recorded during tasks with ambiguous stimuli to better understand cognitive mechanisms and develop human–computer interfaces. The identified correlates can be used as objective indicators of task performance efficiency.

However, this study has several limitations that should be considered when interpreting the results. The primary limitation is the relatively small sample size, which may reduce statistical power and limit the generalizability of the findings. Also, the sample was not balanced in terms of gender distribution, which may have influenced the ability to detect potential sex-related differences in oculomotor patterns. However, within the available data, no significant gender-based differences were observed in task performance or eye-tracking metrics. Additionally, the study focuses on a single age group and one type of task, necessitating further research to broaden the applicability of the results.

5 Conclusions

Our study demonstrates that the dynamics of behavioral and physiological characteristics, including error rate, reaction time, and metrics recorded through eye tracking, are significant indicators of the efficiency of processing ambiguous visual information. Data analysis revealed that a reduction in errors and reaction time correlates with participants' learning during the experiment, despite an increase in fatigue levels.

These findings are valuable for the development of brain-computer interfaces, as the identified biomarkers, such as fixation duration and pupil size changes, can serve as objective indicators of cognitive load and task performance efficiency.

Thus, our results contribute to the understanding of certain neurophysiological mechanisms underlying the processing of ambiguous sensory information. At the same time, future studies could further investigate the identified patterns by considering various age groups and task types to generalize the findings and enhance the practical applicability of these indicators.

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Availability of data and materials The data presented in this study are available on request from the corresponding author.

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