The Effects of Stimulus Intensity and Pupil Size on Event-related Potentials (ERPs)

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Abstract

The visual process is influenced by a myriad of factors. One prominent factor is the amount of light that is cast onto the retina. The amount of light that enters the eye is further determined by multiple factors. In the current study, we examined three of these factors. We aimed to investigate the effects of stimulus intensity (here operationalised as stimulus luminance), spontaneous pupil size, and pupil-size slope on the visual process as captured through electroencephalographic (EEG) signals, to investigate how an influx of light impacts visual processing. Participants (n = 10) were presented with full-monitor flashes of varying luminance for two sessions of thirty minutes. EEG signals were measured with 26 scalp electrodes. Simultaneously, pupil size and pupil size change were recorded. We found that stimulus intensity reliably affected both signal amplitude and peak latency of EEG components. Spontaneous pupil size at stimulus presentation only displayed one significant cluster in the temporal channel group, which may be a spurious result and needs replication. Pupil size slope at stimulus presentation displayed two significant clusters in central and occipital channel groups. For pupil dilation at stimulus presentation, amplitude was lower as compared to pupil constriction at stimulus presentation. No effects of pupil size slope on latency could be detected. This indicates that the visual process, at a level that EEG signals can capture, are very sensitive to changes in visual input corresponding to external stimuli, but less so for changes in bodily states, such as pupil size.

***Keywords**:* pupil size, pupillometry, visual process, EEG, stimulus intensity

The Effects of Stimulus Intensity and Pupil Size on Event-related Potentials (ERPs)

Visual processing is one of the most fundamental mechanisms of human perception, and remains an active area of research. Various factors, such as stimulus properties, physiological changes or even psychosensory states can influence how visual information is processed by the brain. Understanding the interplay of these factors as well as their effect on visual processing is crucial to improve our understanding.

One factor that has been studied in relation to the visual process is stimulus intensity, which is closely related to stimulus contrast. Previous research has established effects of stimulus luminance on amplitude, latency and topography of EEG signals. Johannes and colleagues (1995) examined the effects of stimulus luminance on ERPs. Participants were presented with unilaterally flashing vertical bar stimuli of two different luminance levels, which they had to covertly attend. EEG signals were recorded from 28 channel sites spanning frontal, central, temporal, parietal and occipital areas. Results showed that, independent of attention, brighter stimuli generally corresponded to higher ERP amplitudes for posterior, parietal and occipital components. In some cases, brighter stimuli also seem to correspond to shorter peak-latencies in EEG components (Johannes et al., 1995; Lines et al, 1984).

Apart from stimulus properties, spontaneous pupil size at stimulus presentation is an impactful factor on visual processing. Pupil size plays a crucial role in the earliest stages of visual processing, by determining how much light enters our eyes. However, the exact role that pupil size plays in visual perception is not yet fully understood (Mathôt et al., 2023). This arises out of a difficulty to establish clear causal connections between pupil size and visual perception, as pupil size can be related to cognitive activity in various ways. For example, pupil size and pupil-size change can relate to physiological triggers such as the *pupillary light response* or the *pupil near response*. But this relationship is not unidirectional; pupil size affects visual processing by determining the amount of light that is cast onto the retina, but

can also change in *response* to changes in visual input. The *pupillary light response* has further been shown to be modulated by higher cognitive functions (Hustá et al., 2019). Pupil size has also been demonstrated to reflect a multitude of (higher-level) cognitive factors such as mental effort (Mathôt, 2018; Montefusco-Siegmund et al., 2022). This *psychosensory pupil response* seems to reflect overall arousal, and further underlines that pupil size, as well as pupil dilation and constriction, are not exclusively driven by external stimuli, but can possibly also reflect cognitive processes or other psychosensory states. Crucially, these factors can affect performance on visual tasks in ways unrelated to pupil size. Because of this, whenever a correlation between pupil size and some aspect of visual processing is found, it is difficult to say whether pupil size affects visual processing, or the other way around.

Regarding the effects of pupil size on the visual process, two distinct lines of research exist. Pupil-linked arousal studies assume that pupil size reflects a state of arousal (Grujic et al., 2024). Any correlations between pupil size and a dependent measure would be considered to be mediated by arousal, and not understood as a direct effect of pupil size. Studies in this domain have demonstrated a correlation between EEG signal and spontaneous fluctuations in pupil size. In rhesus macaque monkeys, spontaneous pupil size seems to be related to neural activity in the locus coeruleus, inferior colliculus, superior colliculus, anterior cingulate cortex, and posterior cingulate cortex (Joshi et al., 2016). This may imply that pupil-size changes could be indicative of coordinated activity across brain regions, which might possibly impact EEG components.

A second line of research focuses on purely optical effects of pupil size on visual processing. In contrast to pupil-linked arousal studies, any correlations between pupil size and a dependent measure would *not* be attributed to arousal. For example, results indicating increased task performance co-occurring with a relatively large pupil size would not be assumed to be an effect of arousal (e.g., more mental effort being employed), but of more

light entering the eye. Bombeke and colleagues (2016) investigated the effects of pupil size on the primary visual cortex (V1) response. Their results demonstrated an inverse relationship between pupil size and the C1 component within EEG signals, which is believed to reflect early-stage visual processing in the V1 area. This effect was more pronounced in the upper visual field of participants, and seemed to be independent of possible psychological factors such as attention. Suzuki and colleagues (2019) investigated the effects of the glare illusion and pupil constriction on steady-state visual evoked potentials (SSVEPs). Participants were presented with flickering dots embedded in glare illusion stimuli of varying luminance, or a control stimulus. Results indicated that SSVEP amplitude decreased for relatively smaller pupil sizes. Mathôt and colleagues (2023) investigated the effects of pupil size on visual processing. Pupil size was induced by presenting participants with red or blue stimuli of equal luminance, which results in changes in pupil size because of differential activation of intrinsically photosensitive retinal ganglion cells (ipRGCs). They also examined spontaneous fluctuations in pupil size, independent of the red/blue inducers. Results indicated that both induced and spontaneous pupil size affect EEG signals in the beta frequency band, mainly over the occipital cortex. All three studies illustrate purely optical effects of pupil size on cortical visual processing that are discernible in EEG signals.

We currently lack a comprehensive overview of general effects of spontaneous pupil size on EEG components measuring visual processing. The multitude of factors that impact both EEG components and pupil size make disentangling the factors and effects challenging.

To date, effects of pupil-size slope (indicating pupil dilation or constriction) on ERPs have not been systematically investigated. Pupil-size slope has nevertheless been associated with levels of arousal outside of the context of EEG signals (Crombie et al., 2024; Mathôt, 2018). In the same study that is the focus of this paper, we also recorded electroretinographic signals from electrodes placed close to participants' eyes, while they were presented with

full-screen flashes of light (Mathôt et al., 2024). This data will not be discussed here, but in brief, we found that the direction of pupil-size change at the moment of stimulus presentation had an effect on early retinal responses. While this result does not predict effects on ERPs, we find this relationship worth exploring, as a dynamic measure of pupillary activity might add to our overall understanding of the visual process.

The current study aims to examine the effects of all three factors described above (stimulus intensity, spontaneous pupil size and pupil-size slope) on EEG signals at all recorded electrode sites, that is, occipital, central, parietal, temporal, and frontal electrodes. We used a within-subject experimental design, where participants (n = 10) completed a task which included a presentation of full-monitor flashes at various luminance levels in which an occasional target stimulus was embedded. Simultaneously, pupil size and EEG activity were recorded. Effects were examined for statistical significance using a cluster-based permutation test for groups of electrodes. Based on previous findings, we generally hypothesised that an increase in stimulus intensity and pupil size may correlate with stronger deflections and decreased peak latency of EEG components.

Methods

Participants

A total of 10 participants (6 females, 4 males, $M_{age} = 25.5$) completed the experiment, including the author and thesis supervisor. All participants were healthy with normal vision. Seven participants were students at the University of Groningen. The remaining participants were staff members at the University of Groningen. One additional participant was tested, but had to be excluded due to an excessive amount of blinks during the trials. As electrodes were placed close to the participants' eyes, which could further be assumed to cause moderate temporary discomfort, we decided to aim for a sample size of 10.

Research Design and Procedure

Participants completed the experiment in OpenSesame 4.0 (Mathôt et al., 2012), using the PsychoPy (Peirce, 2007) backend for display presentation and PyGaze (Dalmaijer et al., 2014) for eye tracking.

Participants were presented with either full-screen flashes of varying luminance intensity, or flashes in hemifields of the screen in full intensity. Here we report only the results of the full-screen flashes (see supplementary results of Mathôt et al. 2024 for results for hemifield flashes). To ensure a constant level of engagement, participants were instructed to detect a stimulus which was embedded in the full-screen flashes in 10% of the trials. The experiment was conducted on a desktop with a 27” LCD monitor, with a 1920 × 1080 pixels resolution and a refresh rate of 60 Hz. Participants sat at a distance of approximately 76 cm from the screen.

We simultaneously recorded pupil size and electrical brain activity, as well as electrical retinal activity. Pupil size and gaze position were recorded from the participants’ right eye at 1000 Hz, on an EyeLink 1000 (SR Research) eye tracker. EEG data were recorded at 1000 Hz, with 26 channels placed in line with the standard 10-20 system (see Figure 1). A TMSI REFA 32 amplifier was controlled by OpenViBE data acquisition software (Renard et al., 2010). The signal was re-referenced off-line against two electrodes placed on the participants’ mastoids. Four additional electrodes were placed above and below participants’ eyes to record electrical activity of the retina (See Figure 2. The data from these electrodes were not analysed in this study, but see Mathôt et al., 2024.). Upper electrodes were attached approximately on, or slightly above the upper lid fold. Lower electrodes were placed immediately below the eye, approximately on or slightly below the lower lid fold. The eye electrodes were placed as close to the eye as possible, without obstructing regular vision.

At the time of recording, all electrodes were referenced against the grand average signal, and additionally re-referenced offline against the average of the left and right mastoid electrodes.

Electrodes were grouped into six groups (frontal, central, temporal, centroparietal, parietal and occipital group; see Figure 1) for analysis. This was done based on a subjective visual inspection of how similar the EEG signal was within the 750 ms time window following stimulus onset. Similar electrodes were grouped together.

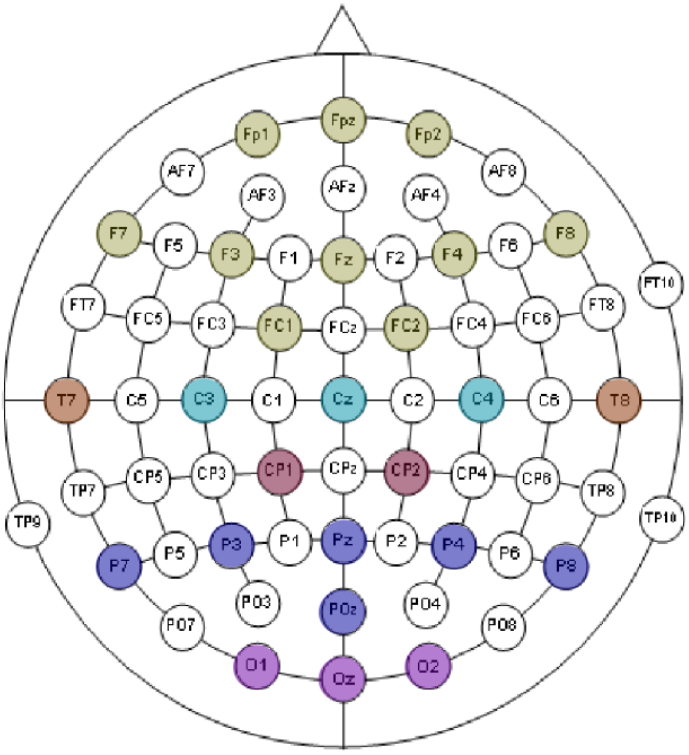

Figure 1. *Distribution of recorded channels using the standard 10/20 system. We recorded 26 scalp electrodes, next to two mastoid reference electrodes and four eye electrodes. Electrodes were grouped for analysis, as demonstrated here by different colours. Figure adapted from Oostenveld and colleagues (2019).*

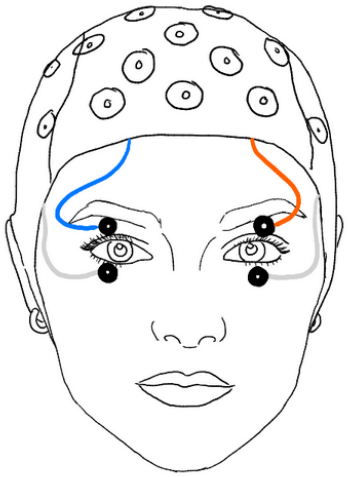

Figure 2. *Overall EEG-setup including the placement of the four eye electrodes.*

Experimental procedure

The experiment was conducted in a dimly lit room with illumination levels below 1 lux. The experiment consisted of two thirty-minute sessions. In each session, participants completed five blocks of 100 trials.

Trials began with a fixation dot in the centre of a black screen. Then, a white flash was presented. Flashes could be either covering the full screen, with five varying luminance levels, or half of the screen (upper/lower or left/right half) at full luminance. Flashes were presented for 100ms. In 10% of the trials, a small colourful patch was embedded within the full-screen flash stimulus. Participants were instructed to press the spacebar when they detected this stimulus. Response time or accuracy on this task was not further investigated, as the task merely served to keep participants engaged.

Data preprocessing

Data was analysed using the python packages *eeg_eyetracking_parser* (Mathôt et al., 2023), *eyelinkparser* (Mathôt & Vilotijević, 2022), *autoreject* (Jas et al., 2017) and *time_series_test* (Mathôt & Vilotijević, 2022). The *eeg_eyetracking_parser* (Mathôt et al.,

2023) package provided general EEG processing, while *eyelinkparser* (Mathôt & Vilotijević, 2022) specialises in analysing eye movements and pupil size. To identify and rectify problematic EEG channels and epochs, the *autoreject* (Jas et al., 2017) package was employed. Additionally, the *time_series_test* (Mathôt & Vilotijević, 2022) package was used to perform cluster-based permutation tests during the analysis.

Data preprocessing procedures varied, depending on the type of data analysed. For the analysis of pupil-size data, Mathôt and Vilotijevic's (2022) recommendations were followed. Whenever possible, missing or invalid data were interpolated using cubic-spline interpolation. Linear interpolation was employed wherever cubic-spline interpolation was not feasible. Whenever interpolation was impossible altogether, or the duration of missing data exceeded 500 ms and likely did not indicate a blink, data were removed. Pupil size was then converted to millimetres, without an application of baseline correction.

EEG data underwent fully automated preprocessing. By default, data was re-referenced to the average of the two mastoid channels. Muscle artefacts, identifiable as bursts of high-frequency activity, were marked as bad using the respective MNE function, with a z-threshold of 5. Data were filtered with a 0.1 - 40 Hz bandpass filter. Bad channels were identified using a RANSAC algorithm, which identifies channels as bad when the interpolation from neighbouring channels poorly predicts its data (Bigdely-Shamlo et al., 2015). The EEG signal was baseline-corrected using the 100 ms preceding stimulus onset as the baseline period. The signal was defined as the average of the electrode group, as described above, which was also referenced against the mean of the left and right mastoid.

Trials were excluded based on multiple criteria. All trials in which a target was presented were excluded from analysis. Exclusion also followed if pupil-size data was missing for 150 ms after stimulus onset or if mean pupil size, mean pupil-size change or average amplitude 15 - 40 ms post-stimulus strayed more than three standard deviations from

the respective participants' mean value. Further, trials were excluded in which EyeLink's built-in algorithm detected a blink within 500 ms after stimulus onset. A total of 7749 trials (77.5%) remained for analysis after exclusion. Analysis was limited to a 750 ms time window after stimulus onset.

Statistical analysis involved cluster-based permutation tests based on linear mixed effects models with fixed effects of stimulus intensity, pupil size, and pupil-size-change (constricting or dilating), and using voltage as dependent measure. For pupil size, we created five equally sized bins per participant. For pupil-size change, we divided trials into constricting (negative slope) or dilating (positive or zero slope). Models included by-participant random intercepts, without random slopes, and clusters were identified using a $p < .05$ criterion.

Results

Stimulus intensity showed significant clusters in all channel groups. Below is a more detailed description of the clusters; however, we will focus on general observations and make no attempt to interpret individual cluster results.

For the frontal group, a large significant cluster emerged at 110 ms, which lasted until 380 ms ($p < 0.001$) after stimulus onset. The amplitude of the components within this cluster scaled strongly with increasing stimulus intensity. Further, latency seemed to be moderately affected.

For the central group, the first cluster emerged at 50 ms and the last cluster lasted until 280 ms (50-100 ms: $p = 0.045$; 150-280 ms: $p = 0.003$) after stimulus onset. For the temporal group, the first cluster emerged at 60 ms and the last cluster lasted until 240 ms (60-110 ms: $p = 0.03$; 160-240 ms: $p = 0.006$) after stimulus onset. In both channel groups, increasing stimulus intensity affected both amplitude and latency of components. Effects of increased

stimulus intensity differed between components; for some components, higher stimulus intensities resulted in weaker deflections, and for other components, higher stimulus intensities resulted in stronger deflections. Increased stimulus intensity seemed to generally decrease component latency across components.

For both the centro-parietal (50-90 ms: $p = 0.958$; 150-280 ms: $p = 0.998$, 430-630 ms: $p = 0.997$) and the parietal group (50-90 ms: $p = 0.047$; 150-230 ms: $p = 0.005$; 430-480 ms: $p = 0.047$; 490-630 ms: $p = 0.009$), the first cluster emerged at 50 ms and the last cluster lasted until 630 ms after stimulus onset. In both channel groups, increasing stimulus intensity affected both amplitude and latency of components. Effects of increased stimulus intensity differed between components; for some components, higher stimulus intensities resulted in weaker deflections, and for other components, higher stimulus intensities resulted in stronger deflections. Increased stimulus intensity seemed to generally decrease component latency across components.

For the occipital group, the first cluster emerged at 40 ms and the last cluster lasted until 751 ms (40-80 ms: $p = 0.035$, 130-170, $p = 0.04$, 180-230, $p = 0.031$, 330-370 ms: $p = 0.041$, 380-751 ms: $p < 0.001$) after stimulus onset. Increased stimulus intensity affected both amplitude and latency of components. Effects of increased stimulus intensity differed between components; for some components, higher stimulus intensities resulted in weaker deflections, and for other components, higher stimulus intensities resulted in stronger deflections. Effects on latency also differed between components, with some components displaying higher latency for increased stimulus intensity, and other components displaying decreased latency for increased stimulus intensity.

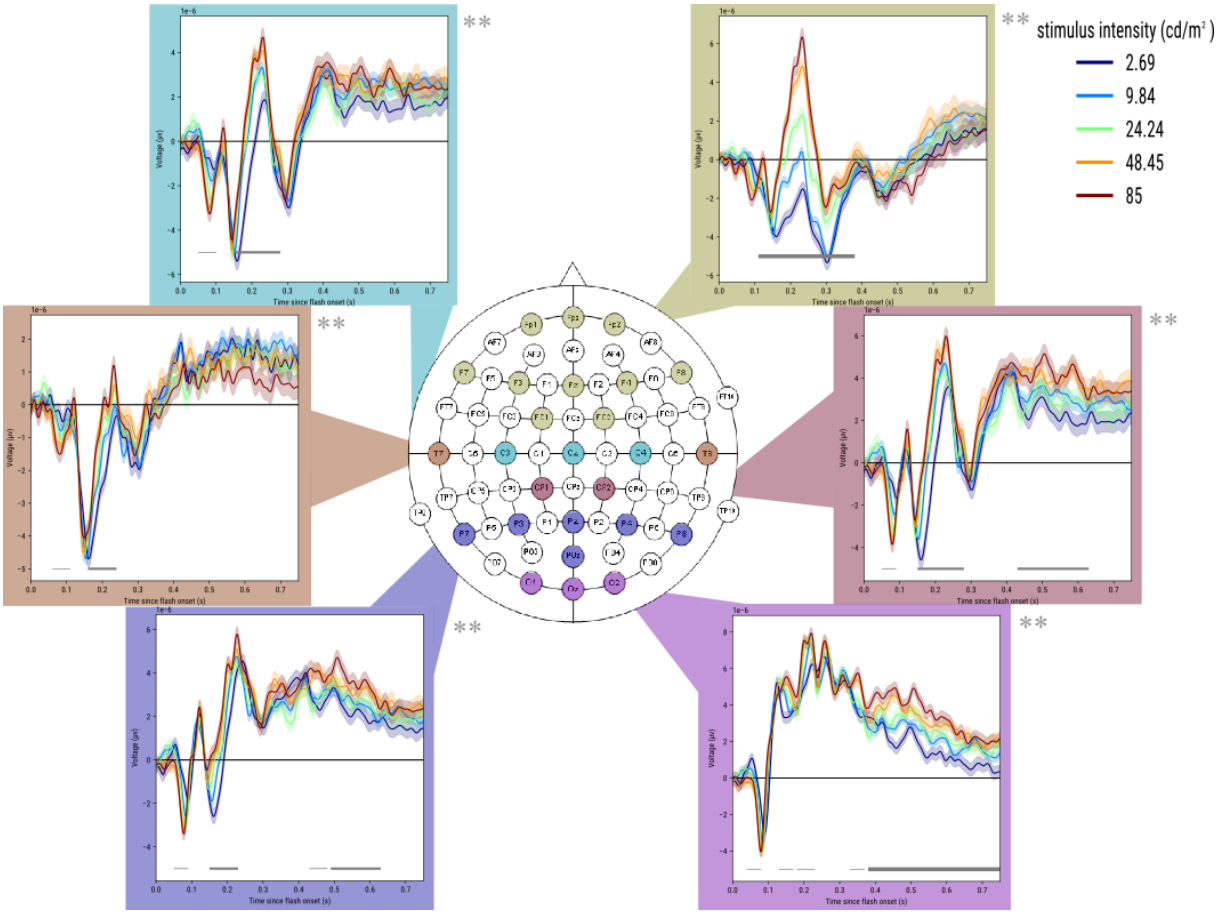

Figure 3. *The effects of stimulus intensity on the different channel groups. Colour coding on the central scalp map indicates which electrodes were grouped together (see main text for details). The panels indicate the mean EEG signal over time for individual electrode groups, separately for each intensity level. Error bands indicate grand standard error of the mean. Horizontal lines indicate significant clusters. Groups with significant clusters are also marked **. Starting from the top right graph moving clockwise; Frontal, centro-parietal, occipital, parietal, temporal and central channels. Figure adapted from Oostenveld and colleagues (2019).*

Pupil size showed one significant cluster in the temporal channels. The cluster emerged at 650 ms and lasted until 690 ms (p = 0.039) after stimulus onset. Importantly, we did not correct for multiple comparisons at the level of separate analyses (only within each analysis) and as such it is possible that this cluster is a spurious result. Increasing pupil size

corresponded to lower amplitudes in this cluster. Pupil size seemed to have no effect on component latency.

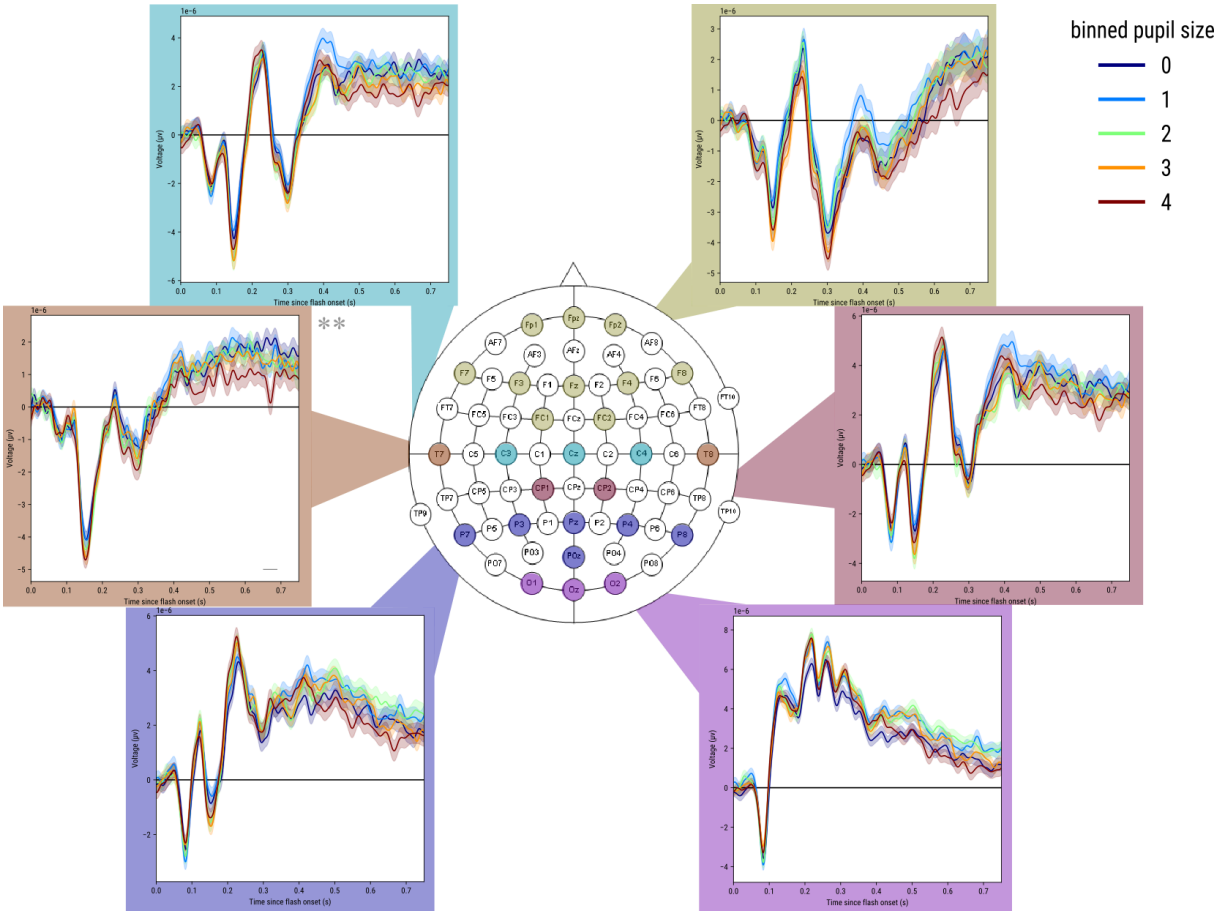

Figure 4. *The effect of binned pupil size on the different channel groups. Colour coding on the central scalp map indicates which electrodes were grouped together (see main text for details). The panels indicate the mean EEG signal over time for individual electrode groups, separately for each pupil-size bin. Error bands indicate grand standard error of the mean. Horizontal lines indicate significant clusters. Groups with significant clusters are also marked **. Starting from the top right graph moving clockwise; Frontal, centro-parietal, occipital, parietal, temporal and central channels. Figure adapted from Oostenveld and colleagues (2019).*

Pupil-size slope showed two significant clusters among the channel groups. For the occipital group, a significant cluster emerged at 610 ms and lasted until 680 ms (p = 0.033)

after stimulus onset. Negative pupil-size slope (pupil constriction) corresponded to a higher amplitude in this cluster. Pupil-size slope seemed to have no effect on component latency.

For the central group, a significant cluster emerged at 580 ms and lasted until 680 ms (p = 0.024) after stimulus onset. Negative pupil slope (pupil constriction) corresponded to a higher amplitude in this cluster. Pupil-size slope seemed to have no effect on component latency.

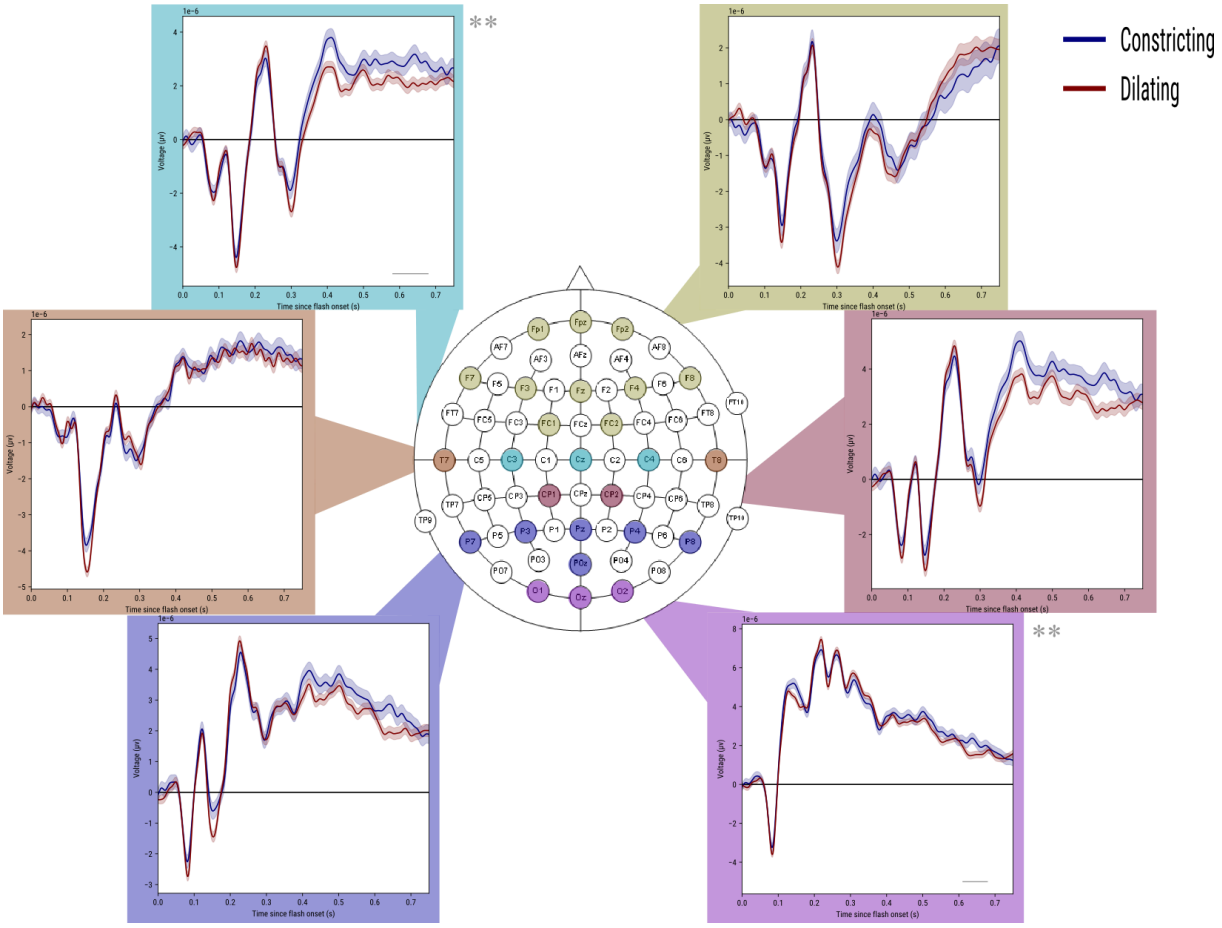

Figure 5. *The effects of pupil dilation/constriction on the different channel groups. Colour coding on the central scalp map indicates which electrodes were grouped together (see main text for details). The panels indicate the mean EEG signal over time for individual electrode groups, separately for constriction and dilation. Error bands indicate grand standard error of the mean. Horizontal lines indicate significant clusters. Groups with significant clusters are also marked **. Starting from the top right graph moving clockwise; Frontal, centro-parietal, occipital, parietal, temporal and central channels. Figure adapted from Oostenveld and colleagues (2019).*

Discussion

Stimulus intensity reliably affected EEG signals across all channel groups. These effects presented at different timepoints within the 750 ms interval we analysed. Further, there was no equivocal, one-directional effect of an increase in stimulus intensity. EEG components displayed increases and decreases in both peak amplitude and latency in response to changes in stimulus intensity. Previous research has established effects in which brighter stimuli systematically correspond to higher amplitudes and shorter latencies of components (Johannes et al., 1995). This effect was replicated in our dataset; in all channel groups, multiple components scaled up in amplitude for increasing stimulus intensity (see Figure 3). However, we also observed the opposite effect for some components. For example, in the central, parietal, centro-parietal and occipital channel groups, the negative deflections occurring around 90 ms scaled down in amplitude for increased stimulus intensity. The overall effect on latency proposed by Johannes and colleagues also replicated in our dataset. For all channels groups, peak latency of components scales down with increased stimulus intensity (see Figure 3). In other words, the effect of stimulus intensity on ERPs is such that latency decreases and amplitude usually increases with increasing stimulus intensity, but the details of this pattern can be complex and variable.

Spontaneous pupil size displayed one significant cluster in the temporal channel group, which we suspect to be a spurious result. When investigating the significant cluster, no clear scaling of either amplitude or latency could be identified (see Figure 4). Pupil size further showed no significant effects on any of the other channel groups. This implies that an increase in light cast onto the retina through spontaneously increasing pupil size did not affect ERPs as measured by EEG in the current study.

The divergent effects of stimulus intensity and spontaneous pupil size raise an interesting point; superficially, increasing the luminance of a stimulus and a larger

spontaneous pupil size both allow more light into the eye (Mathôt et al., 2023). However, only the ‘external’ factor of stimulus intensity displayed significant clusters in all channel groups. If the effects of both factors were exclusively determined by light influx, results would be expected to be more homogeneous. The reason for the discrepancy we found might be related to the concept of brightness constancy. An increase in pupil size does not result in an increase in perceived brightness, even though more light enters the eye (Wardhani et al., 2022). From a functional point of view, this makes sense. Our body needs to be able to identify changes in visual input that correspond to changes in our environment. If a change in pupil size were to perceivably alter the way we see the world, we effectively would not be able to make a distinction between actual changes in the environment and changes in bodily states. Pupil constriction would then be similar to the effect of someone dimming the light in a room. This may account for a lack of effects of spontaneous pupil size on EEG signals.

A similar mechanism helps us perceive the world in a coherent manner even when we move our eyes. Eye movements drastically change the way that visual input projects onto the retina (analogous to how pupil-size changes change the amount and focus of light on the retina). With every eye movement, our retinal image shifts. However, we don’t perceive any noticeable disruption of the retinal image when we move our eyes (Mathôt, 2013). Possible explanations for this phenomenon are the concepts of corollary discharge or efference copy. These concepts propose that a neural copy of the motor command to the eyes is created when we move our eyes. This copy is assumed to be processed by the visual system to compensate for changes in visual input caused by eye movements, resulting in a stable visual percept despite a changing retinal image (Bridgeman, 2007; Wurtz, 2018). A similar mechanism might help our body account for changes in pupil size and prevent any influence on subjective brightness perception, despite changes in retinal light influx (Wardhani et al., 2022).

Pupil-size slope displayed two significant clusters within the central and occipital channel groups. In the significant clusters, pupil dilation at stimulus presentation resulted in lower amplitude as compared to pupils that were constricting at stimulus presentation (see Figure 5). In an analysis of electroretinal signals from the same dataset as presented here (Mathôt et al., 2024), we found that early retinal responses are affected by pupil change direction at the time of stimulus presentation. In the current study, we saw weak effects in two channel groups. The effects of pupil-size slope might thus be limited to earlier stages of the visual process.

Some limitations need to be considered in relation to the current study. The small sample size only afforded us with low power, and thus especially the (lack of) effects we found for the factors of spontaneous pupil size and pupil-size slope should be consolidated with replications. Cluster-based permutation analysis might further be biased towards strong and temporally broader effects. Upon visual inspection, there seem to be possible effects of dilation on component peaks that our statistical analysis did not flag as significant. Additionally, the monitor latency of the experimental monitors used in this experiment should be taken into account. This monitor latency might have introduced a slight temporal shift of the EEG components analysed, which would also affect any classification of components.

In conclusion, it seems that visual processing, as captured here by EEG signal, is very sensitive to changes in visual input that correspond to external changes, such as luminance. However, visual processing, as captured by EEG signals, is not very sensitive to changes in visual input that result from changes in our own body, in this case changes in pupil size, and direction of pupil-size change.

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