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Attention modulates cortical and subcortical responses to auditory deviance: An EEG-pupillometry study in healthy adults

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Abstract

Pupillary and electroencephalographic (EEG) signals can reflect arousal-related responses to violations of temporal auditory regularities, involving locus coeruleus-noradrenergic (LC-NE) system neuromodulation. We combined simultaneous pupillometry and EEG with a local-global auditory paradigm in 26 adults to test whether pupil and event-related potentials (ERPs) show comparable sensitivity to attentional demands. Participants completed active counting and visual interference tasks. During counting, deviants elicited significant pupil dilation for local (44-1232 ms, $p = .0031$; $\Delta = .09$ z) and global violations (288–2000 ms, $p = .0001$; $\Delta = .45$), with ERP effects at Pz (local: 2.51 μV; global: 2.01 μV). Under visual interference, pupil effects were reduced but remained significant for local (0-690 ms, $p = .0247$; $\Delta = .05$) and global violations (446–1818 ms, $p = .0083$; $\Delta = .11$), whereas ERP effects were mostly absent.

These findings suggest that pupil responses remain sensitive to auditory deviance when ERP effects are attenuated.

Introduction

The ability to prioritize goal-directed sensory inputs while concurrently maintaining unattended vigilance for environmental changes is a fundamental evolutionary necessity for both humans and animals (Aston-Jones & Cohen, 2005; Geva et al., 2013). Organisms constantly navigate the trade-off between attentional focusing and the selective concentration of limited cognitive resources. This equilibrium is fundamental for the execution of primary survival-critical tasks, such as threat avoidance (Mobbs et al., 2015). Thus, divided attention enables the passive monitoring of multiple concurrent information streams (Aston-Jones et al., 1999). Since cortical processing capacity is intrinsically constrained, dividing voluntary attention across highly demanding tasks leads to degraded performance and significant cognitive costs (Broadbent, 1958; Lachter et al., 2004; Pashler, 1994; Rogers & Monsell, 1995). From an evolutionary perspective, the existence of a purely selective attentional system would render an organism vulnerable during periods of intense task engagement (e.g., Fishman, 2014; Malmierca et al., 2014). Consequently, survival relies upon the continuous, pre-attentive scanning of the sensory environment (Cornwell et al., 2007; Tiitinen et al., 1994). This enables the automatic detection of deviant, potentially threatening environmental signals without the need for active, voluntary deployment of the central attentional focus (Li & Keil, 2023).

The neural architecture dedicated to environmental monitoring and vigilance is organized hierarchically across a subcortical-cortical axis, balancing rapid autonomic alerting with detailed cortical evaluation (Aston-Jones & Cohen, 2005; Sara & Bouret, 2012). Here, the locus coeruleus-norepinephrine (LC-NE) system acts as a primary neuromodulator (Sara, 2009). LC-NE neurons show both tonic and phasic modes of activity, with phasic responses being particularly relevant for the processing of salient or task-relevant stimuli (Sara & Bouret, 2012; Vazey et al., 2018). Animal electrophysiology has demonstrated that LC-NE activity can occur prior to changes in pupil diameter, thereby supporting the use of pupil

dilation as an indirect marker of LC-NE-related arousal (Joshi et al., 2016). Direct recordings from the human locus coeruleus (LC) are rarely feasible. Therefore, these indirect physiological markers are often used to study LC-NE-related activity, with pupil diameter serving as one potential candidate marker (Costa & Rudebeck, 2016; Joshi & Gold, 2020; Joshi et al., 2016). Simultaneous pupillometry-fMRI studies have demonstrated that pupil fluctuations and task-evoked dilation covary with activity in LC-brainstem regions and broader attentional networks (Alnæs et al., 2014; Joshi & Gold, 2020; Mazancieux et al., 2023; Murphy et al., 2014). Similarly, EEG markers such as the P300 event-related potential (ERP) have been linked to attentional resource allocation and context updating (Donchin & Coles, 1988; Katayama & Polich, 1998; Kok, 2001; Polich, 2007). Thus, the P300 has also been proposed to reflect phasic LC-NE activity during the processing of salient or task-relevant events (Nieuwenhuis et al., 2005, 2011; Polich, 2007).

Combined pupillometry and EEG studies suggest that pupil dilation and P300 ERPs provide complementary, although indirect, markers of LC-NE-related arousal and cognitive processing (Joshi & Gold, 2020; Kim et al., 2026; Larsen & Waters, 2018; Murphy et al., 2011; Reimer et al., 2016). Furthermore, pupil dynamics and P300 potentials have been separately and jointly investigated as markers of cognitive and arousal-related processing across several domains, including novelty and deviance detection (Bekinschtein et al., 2009; Debener et al., 2005; El Karoui et al., 2015; Liao et al., 2016; Mazancieux et al., 2023; Quirins et al., 2018; Sangaré et al., 2023), sensory processing and sensory gain (Larsen & Waters, 2018; McBurney-Lin et al., 2019), attentional state and task engagement (Alnæs et al., 2014; Aminihajibashi et al., 2020; Keene et al., 2022; Strauch et al., 2022), inhibitory control (Dippel et al., 2017; Rondeel et al., 2015; van der Wel & van Steenbergen, 2018), psychological flow (Lu et al., 2023), reaction time and task performance (Murphy et al., 2011), and working memory load (Johnson et al., 2014; Kahneman & Beatty, 1966; Robison & Unsworth, 2019). Nevertheless, the cognitive processes related to these neurophysiological markers are not yet well understood or easily standardized. Thus, their functional interpretation remains context-dependent.

The local-global auditory paradigm provides a useful framework for separating lower-level sensory change detection processing (local novelty) from higher-order regularity processing (global novelty). Local deviance can be defined as the detection of a change within a short stimulus sequence (auditory stimulus with a different pitch), whereas global deviance reflects the violation of an expected sequence pattern over time (Bekinschtein et al., 2009). Local novelty reflects autonomic physiological responses of the nervous system to auditory deviant stimuli, whereas global novelty represents cognitive perceptual processing to an auditory deviant stimulus that differs context-wise (e.g., the probability of a deviant tone appearing within a certain pattern). In EEG studies, it has been shown that local violations are typically associated with early auditory ERP components including mismatch negativity (MMN) activity (Näätänen et al., 2007), whereas global violations elicit later and more spatially distributed responses, often associated with a P3b-like component (Bekinschtein et al., 2009; El Karoui et al., 2015; Wacongne et al., 2011).

Dual-task situations are known to reduce the availability of attentional resources, and the P300 amplitude is especially sensitive to task demands and processing capacity (De Vos & Debener, 2014; Kok, 2001; Polich, 2007; Wickens, 2002). Similarly, pupillometry studies show a related but not identical pattern: sharing attention across tasks often leads to pupil dilation, reflecting greater resource recruitment and higher cognitive control demands (Beatty, 1982; Karatekin et al., 2004; van der Wel & van Steenbergen, 2018), but the phasic pupil response to a specific event may be reduced when that event is task-irrelevant or when attention is prioritized toward another task (Demberg, 2013; Karatekin, 2004; Tapper et al., 2021; Vogels et al., 2018; Zekveld et al., 2018). Thus, dual-tasking does not necessarily produce a simple additive increase in physiological responses. Instead, EEG and pupil dynamics appear to reflect the distribution of resources across competing task demands and significant stimuli (Menicucci et al., 2024; Polich, 2007). Therefore, the robustness of local and global pupil and EEG effects when attention is divided by an additional task in another sensory modality remains unclear. This question is particularly relevant for the local-global paradigm because global deviance detection requires the integration of information across time and trials and may therefore be especially sensitive to attentional demands.

The present study investigated local and global auditory deviance processing in healthy young adults using simultaneous EEG and pupillometry. This study asked whether local and global auditory effects could be detected through pupil dynamics and ERPs. It further asked whether these effects would be attenuated under visual interference. It was hypothesized that local and global deviant stimuli would induce increased pupil dilation and ERP magnitude during the active counting local-global paradigm. In contrast, it was further predicted that deviance-related pupil and ERP responses would be non-significant during a visual interference task, especially at the global level. By combining pupillometry and EEG, this study aimed to clarify whether cortico-subcortical markers of auditory deviance processing show similar or dissociable sensitivity to attentional interference.

Materials and methods

Preregistration

The study was conducted at the Department of Neurology of the University of Oldenburg and Evangelical Hospital Oldenburg. This was a single-center, within-subject study. The hypotheses, methods, and analysis plans of this study were prospectively registered prior to data collection. The preregistration was submitted on October 6th, 2025, and is available at the German Clinical Trials Register (Deutsches Register Klinischer Studien - DRKS) under the ID number DRKS00037752 (https://drks.de/register/de/trial/DRKS00037752/preview).

Participants

The sample size was estimated a priori based on statistical power analysis using RStudio (RStudio PBC, Boston, MA, USA, *version 2022.12.0*) within the R *version 4.4.2* (R Core Team, 2024). The sample-size calculation was based on the confirmatory global pupil-response effect in the single-task active counting condition and assumed a conservative paired effect size of Cohen's d = 0.8 for the cluster-averaged comparison between conditions. Thus, power was estimated by simulation, using a non-parametric cluster-level paired t-test with 10,000 permutations, assuming one temporal cluster, variance $\sigma = 1$, correlation $\rho = 0.5$, and a Bonferroni-corrected local α of 0.0125. This analysis indicated that 26 participants were required to achieve 91% power, with no anticipated dropouts. Thus, 26 healthy individuals (16 women and 10 men) were included in this study. Participants performed an auditory oddball counting task (E1; Experiment 1) and a visual interference task (E2; Experiment 2) while their electrical brain activity and pupil dynamics were recorded. Participants were recruited via posters and flyers in publicly accessible locations and the university online campus platform StudIP. Potential participants could contact the study administrators and were provided with detailed information about the study and screened for inclusion/exclusion criteria.

The inclusion criteria specified an age range between 20 and 30 years (mean = 24.23 years, *SD* = 2.58), as a narrow age range of young adults has been demonstrated to minimize well-known age effects on auditory ERP outcome measures (Polich, 1997; Profant et al., 2019). Furthermore, participants were required to be fluent in German or English and to have normal hearing.

The exclusion criteria were acute or past iritis, previous neurological or psychiatric conditions, relevant ocular diseases (including previous eye surgery, glaucoma, pseudoexfoliation syndrome at the pupillary margin or lens, corneal disease, nonspheroidal pupils, relevant anisocoria), and diabetes mellitus. Participants wearing multifocal contact lenses, reflective glasses, or glasses with shiny jewelry were also excluded. They were also excluded if they used any of the listed centrally acting medications in the table: Effect of drug treatment on the pupil (Kelbsch et al., 2019).

Participants were informed in advance about the study procedure, tasks, experimental methods, and data protection measures. Volunteers provided their written informed consent prior to participation (with the possibility of withdrawal at any time) and were compensated with 10€/h. The experiment was conducted according to the tenets of the Declaration of Helsinki and approved by the Medical Ethics Committee of the University of Oldenburg (approval number: Drs/EK2025/160-01).

Materials

The presentation of stimuli and loudness level threshold detection were programmed and presented using custom MATLAB scripts written in MATLAB *R2025b* (The MathWorks, Inc., 2025). MATLAB was also used for synchronizing the tone sequence with the pupillometer and EEG acquisition, using TTL triggers and Ethernet messages. The setup was installed on a commercial PC equipped with a standard sound card for auditory stimulus delivery.

EEG data were recorded using a wired 128-channel active EEG amplifier system (Brain Products GmbH, Gilching, Germany) with 32 active electrodes (at the 10–20 sites: Fp1, Fp2, F3, F4, F7, F8, FC1, FC2, FC5, FC6, FT9, FT10, Fz, Cz, C3, C4, CP1, CP2, CP5, CP6, T7, T8, TP9, TP10, P3, P4, P7, P8, Pz, O1, O2). The reference and ground electrodes for the EEG system were placed at FCz and AFz, respectively. Impedances were kept below 20 kΩ using an electrolyte gel (Abralyt HiCl, Easycap GmbH, Herrsching, Germany). EEG data were recorded at a sampling rate of 500 Hz with a trigger input/output of 8-bit TTL (LVTTL) signals, 0 to + 5 V (+ 3.3 V), max. 10 mA. The recording software used was BrainVision Recorder, *version 1.22.0001* (Brain Products GmbH, 2020).

Pupil diameter was measured monocularly (left eye) in arbitrary units (a.u.) using the video-based eye-tracking system EyeLink 1000 *version 1.5.2* (SR Research Ltd., 2005–2010) at a sampling rate of 500 Hz. The eye-tracker camera used for this purpose was placed on the table in front of the participants at approximately 1.5 m from the participant's eyes. The participants' heads were fixed in a stationary chin holder to restrict movement. All measurements were performed in a dark room with a panel screen placed at the same viewing distance as the eye-tracker camera. This monitor screen constituted the only source of luminance in the room (monitor luminance produced an ambient illuminance of 10–20 lux).

EEG and EyeLink were synchronized through a stimulus host PC that sent TTL signals to the EEG amplifier via a parallel port and simultaneously sent Ethernet messages to the eye tracker. Thus, TTL onsets were matched with their associated messages to synchronize the two data streams, which marked the onsets of the trial events for data analysis. In addition, the Regularity Awareness Score (RAS) (Bekinschtein et al., 2009) and a custom questionnaire were used to measure subjective awareness and collect personal data.

Tasks

Participants silently performed a modified version of the local-global auditory paradigm (Bekinschtein et al., 2009), adapted to pupillometry (Mazancieux et al., 2023). In this task, a series of auditory stimuli was presented repeatedly in blocks of five through headphones, where the 5th stimulus changed in pitch according to probability. Each five-tone sequence was considered one trial, and all of them were presented in a randomized order for each participant to control for sequence effects (e.g., neural or sensory adaptation).

During the habituation phase, identical stimulus blocks were used. This phase was used to establish an expected sequence (e.g., only five short tones of the same frequency, xxxxx, xxxxx, xxxxx, etc., or a consistently deviating sequence: xxxxY, xxxxY, xxxxY, etc.). The habituation phase lasted approximately 2 min and included 50 identical tone sequences (25 in the form xxxxx for the first set of blocks and 25 in the form xxxxY for the second set).

During the test phase, standard stimuli appeared 80% of the time and deviant stimuli occurred 20% of the time in an irregular sequence (a xxxxY sequence following the xxxxx, xxxxx, xxxxx blocks, or a xxxxx

sequence following the xxxxY, xxxxY, xxxxY blocks). Thus, deviance within a trial constitutes local deviance (fifth tone different in pitch), whereas deviance based on the consistency of prior consecutive blocks is considered to be global deviance. The test phase lasted approximately 6 min and included 220 tone sequences (110 in the form of xxxxx for the first set of blocks and 110 in the form of xxxxY for the second set).

In the first experiment, participants were asked to silently count the deviant tones and report the total number of deviant tones at the end. Thus, the first set of blocks of 135 five-tone patterns (25 habituation + 110 test trials, 80/20 global standard/deviant) were presented while participants were looking at a fixation cross. The reverse probability was presented in the second set of blocks (25 habituation + 110 test trials, 80/20 global standard/deviant). All subjects heard the two possible block types once. This is hereafter referred to as the first experiment (active counting single task).

For the second experiment, the same version of the local-global paradigm was presented, with the addition of a visual interference task. Here, participants were still looking at a fixation cross and were asked to ignore the background tones while a series of consecutive figures (triangles, squares, diamonds, and circles) appeared on the screen. They were required to detect the circle by pressing the spacebar as quickly as possible. This task distracts from auditory processes and can be used to test whether global effects are still detectable and independent of sensory modality. To minimize luminance-driven pupil changes, stimuli were presented on a dark-grey background; the fixation cross and bold outlines of the figure shapes were the only sources of luminance variation. Figure shapes were presented at a rate of 1000 ms to avoid flickering as much as possible. After each task, the participants completed an awareness assessment questionnaire. A schematic representation of the experimental design is shown in Fig. 1.

The sound sequences were delivered through headphones with a sound intensity of 30 dB above the hearing threshold. This threshold was measured individually, and reflects the lowest sound intensity that a participant is capable of perceiving within a comfortable loudness level. The effective timing was a Stimulus Onset Asynchrony (SOA) of 365 ms between sounds, making a total duration of 1710 ms per trial with an inter-trial interval (ITI) of 1770 ms. Each sound was composed of three sinusoidal tones (either 350, 700, and 1400 Hz, hereafter referred to as sound "x"; or 500 Hz, 1000 Hz, and 2000 Hz, hereafter referred to as sound "Y").

Procedure

Data were collected at the Department of Neurology laboratory at the Evangelical Hospital Oldenburg. Participants were instructed to come to the appointment well rested and to avoid intensive exercise, alcohol, and coffee on the day before testing. At the beginning, participants completed demographic and personal-information questionnaires and provided written informed consent. EEG recording was then prepared (cap montage, impedance measurements, resting state EEG). Next, headphones were placed above the EEG cap and the individual hearing threshold was determined. During measurements,

participants sat on a chair and placed their head on a chin rest. Participants were asked to look at the fixation cross for eye tracker calibration. EEG preparation, pupil calibration measurements, and questionnaires took approximately 30 to 40 min.

After the setup, the participants performed the first experiment (counting task). This included the habituation phase for familiarization (only xxxxx trials), followed by the testing phase, where participants counted the frequency of deviant stimuli for the first set of blocks (80% of xxxxx, 20% of xxxxY). Afterwards, participants took a 1–2 min break. An inverse habituation phase (only xxxxY trials) was then followed by a new set of blocks (80% of xxxxY, 20% of xxxxx). After completion, the participants took another 5 to 6 minutes break. Subsequently, participants performed the second experiment (visual interference task), where they had to react to the visual target stimulus (circle) while listening to the background sounds (local-global paradigm without attentive counting).

Each experiment lasted approximately 16 min. After the recording was completed, the EEG cap was removed, and the participants had the opportunity to wash their hair. Participants then completed the RAS questionnaire and a remuneration sheet for personal information. Overall, the recording sessions, including preparation, calibration, and follow-up, lasted approximately 90 to 120 min per participant.

Data analysis

The EEG data were processed using EEGLAB *version 2023.0* (Delorme & Makeig, 2004) and custom MATLAB scripts (The MathWorks, Inc., 2025). Pupil data preprocessing was performed using custom MATLAB scripts. An overview of the processing steps is presented in Supplementary Fig. 1.

Pupil preprocessing and response parameterization

EyeLink messages were used to identify the onset of the stimulus in each auditory sequence, and pupil segments were time-locked to the onset of the 5th tone in each trial. The pupil-preprocessing pipeline comprised the following steps. In the raw data, blink periods were detected by the EyeLink system with an extended margin of 50 ms before and after each blink. The pupil signal was then linearly interpolated across these blink intervals to handle the missing data. The continuous pupil signal was then low-pass filtered at 5 Hz (second-order Butterworth filter). Data were epoched from − 500 to 2000 ms relative to the onset of the fifth tone, and baseline correction was applied using the − 500 to 0 ms pre-stimulus interval. Epochs were rejected when blink-contaminated samples exceeded 20% of epoch duration. Finally, the retained pupil epochs were normalized using *z*-score transformation and averaged within each condition for each participant before group-level averaging separately for each experiment. No additional corrections were applied. More details on pupil preprocessing outcomes are presented in Supplementary Table 1.

The main time-domain features of the pupil data were the pre-processed pupil dynamics relative to the onset of the 5th tone. It was investigated whether pupil size was different for local and global effects

(standard vs. deviant trials).

Across both experiments, an average of 8.95% of the recorded pupil epochs was discarded during preprocessing, resulting in 245.83 ± 5.12 (mean ± *SEM*) remaining trials per participant and experiment for averaging purposes. Separately, this corresponded to 243.85 ± 7.79 trials in the counting task (9.69% rejected) and 247.81 ± 6.79 trials in the visual interference task (8.22% rejected). Pupil dynamics were then quantified by averaging *z*-scored pupil values across retained trials for each participant and statistically evaluated over the 0-2000 ms interval relative to the onset of the fifth sound.

To evaluate pupil dynamics, we analyzed the mean z-transformed values across the post-stimulus analysis window (0 to 2000 ms), per trial and participant, and then took the grand average. The larger time period was chosen to compensate for the slower pupil dynamics in comparison with EEG evoked responses. Pupil latencies were parameterized as the time point at which the z-scored pupil response peaked for each participant within the time window and the mean across participants. Statistical analysis was performed on mean samples, consecutive samples, and latencies to compare across conditions, as was done with ERPs. Local effects were computed by comparing local standard and deviant patterns, whereas global effects were computed by comparing frequent and rare patterns (deviance based on probability).

EEG preprocessing and ERP component parameterization

First, channels exceeding a root mean square (*RMS*) of more than 1.5 standard deviations (*SD*) above the mean were flagged as bad and rejected. The remaining data were high-pass filtered at 2 Hz (order 415) and low-pass filtered at 30 Hz (order 111) using zero-phase finite impulse response (FIR) filters (*pop eegfiltnew()*). An extended infomax independent component analysis (ICA) was then applied to the continuous filtered data, and the resulting ICA weights were applied to the unfiltered continuous raw data.

Second, continuous raw data were filtered at 0.5 Hz (order 4127) and 20 Hz (order 331) using FIR filters (*pop eegfiltnew()*). The filtered data were epoched from − 2600 to 700 ms relative to the onset of the 5th tone and baseline-corrected (from − 2600 to -1800 ms). The independent components were automatically labeled as containing artifacts using ICLabel (*version 1.3*) (Pion-Tonachini et al., 2019). Bad components were identified if they exceeded a threshold of 90% for 'eye', 'heart', and 'line noise' artifacts, 30% for 'muscle', and finally 50% for 'channel noise' and 'other' (*pop_iclabel(), pop_icflag()*, and *pop_viewprops()*). The corresponding component activities were then removed from the data by the joint back-projection of all remaining components (*pop_subcomp()*). Residual artifact epochs were identified and rejected using an amplitude threshold of ± 120 μV (*pop_rejepoch()*). Spherical interpolation was then used to replace the rejected channel data (*pop_interp()*). Data were referenced to the common average (*pop_reref()*). Finally, the EEG data were averaged across trials to obtain the ERPs. Detailed results of the data loss during EEG preprocessing are presented in Supplementary Table 2.

The main time-domain features of the EEG recordings were the ERP amplitudes. We also investigated whether ERPs differed in morphology or location between local and global conditions. Across both experiments, an average of 1.61% of the recorded EEG epochs was discarded during preprocessing, resulting in a mean of 265.65 ± 0.89 remaining trials per participant and experiment for averaging, with a range of 239–270 trials. Separately, this corresponded to 266.58 ± 0.96 retained trials in the counting task (1.27% rejected) and 264.73 ± 1.49 retained trials in the visual interference task (1.95% rejected). ERPs were then obtained for all channels by averaging single-trial amplitude values within each participant and statistically evaluated over the 0-700 ms interval relative to the onset of the fifth sound of each trial.

For ERP component evaluation, we calculated mean amplitudes per participant, at the channels of interest (Pz and Fz), within significant windows after the onset of the 5th stimulus sound. Corresponding latencies were parameterized as the time point where the ERP peaked per participant. These parameters were then compared across the four conditions: local standard, local deviant, global standard, and global deviant.

Statistics and Reproducibility

We measured scalp ERPs and pupil dynamics to evaluate the feasibility of detecting local-global effects at the group level. Descriptive results are reported as mean (*M*) ± standard error of the mean (*SEM*); participant age and preprocessing parameters used are reported as mean (*M*) and standard deviation (*SD*). Before conducting parametric analyses, the relevant distributions were assessed for normality using Lilliefors tests (Lilliefors, 1967). All *t* tests and permutation tests were two-sided, and *n* denotes the number of participants contributing to each analysis. The alpha level of significance was set at 0.05 for both pupil and EEG analyses in both group and individual-level statistical tests. The local-global design comprised two within-subject factors: local (standard vs. deviant) and global (frequent/global standard vs. rare/global deviant). Group-level local, global, and local-by-global interaction effects were tested at each time sample using participant-level condition averages and, for EEG, at each electrode. Multiple comparisons were controlled using 10,000-permutation family-wise error (FWE) procedures. A permutation-based max-|*t*| FWE procedure across electrodes and time for ERP components was used, and a cluster-based permutation FWE procedure across time for pupil dynamic differences. The Holm-Bonferroni correction method (Holm, 1979) was used to adjust the between-task comparisons across experiments.

At the individual level, separate within-participant analyses were performed descriptively on single-trial EEG amplitudes and single-trial pupil responses. After balancing trial numbers, local and global conditions were compared using two-sided unpaired Student's t-tests (Student, 1908) at each time sample and, for EEG, at each electrode. Thus, individual effects were retained when $p \leq .05$ persisted for at least 20 consecutive samples, corresponding to approximately 40 ms at 500 Hz for both EEG and pupil signals. EEG effects additionally had to involve at least five electrodes (adapted criterion from Bekinschtein et al., 2009 to the present 32-channel montage). For visualization, retained p-values were

converted into a statistical significance index (SSI), with six significance-level bins: 0 for non-significant time points, and increasing levels for $p \leq .05$, $p \leq .01$, $p \leq .005$, $p \leq .001$, $p \leq .0005$, and $p \leq .0001$. The SSI was subsequently averaged across participants.

For both signals, trials were classified into four elementary conditions: frequent local standard, rare local standard, frequent local deviant, and rare local deviant. Local effects contrasted local-deviant with local-standard responses, whereas global effects contrasted rare, globally deviant responses with frequent, globally standard responses. The local-by-global interaction compared the local effect across global contexts: [(rare local deviant − rare local standard) − (frequent local deviant − frequent local standard)]. All analyses were time-locked to the onset of the fifth tone.

Statistical analysis of pupil data

At the group level, pupil statistics were computed from 0 to 2000 ms after the onset of the fifth tone. For each participant and experiment, subject-level epoch-based pupil responses were computed for local and global trials (standards and deviants) to isolate phasic stimulus-evoked changes in pupil size. Local and global effects were tested using two-tailed paired-sample tests across participants at each time point. Statistical significance was assessed using non-parametric cluster-based permutation tests across time, following the logic of Mazancieux et al. (2023), as outlined below. First, candidate clusters were defined as consecutive time samples with uncorrected $p \leq .05$. Cluster-level FWE correction was performed, in which the two conditions were randomly swapped within participants. For each permutation, the largest cluster observed by chance was stored, creating a null distribution of the cluster sizes. The observed clusters were then compared against this null distribution to obtain FWE-corrected cluster *p*-values. Clusters were considered significant when corrected $p\text{FWE} \leq .05$. For local-global interaction effects, the contrast was tested using the same group-level paired cluster-based permutation procedure described.

For summary analyses, significant group-level cluster time windows (independent for each experiment) were used to analyze subject-level peak latency and mean z-scored pupil size between experiments. For local and global responses separately, these measures were analyzed using 2 × 2 repeated-measures ANOVAs with the within-subject factors task (counting vs. visual interference) and condition (standard vs. deviant) (Fisher, 1925). The ANOVA was followed by paired-samples t-tests comparing the two tasks separately for standard and deviant responses. Within each effect and measure, Holm correction was applied across the two paired comparisons and the task × condition interaction (Holm, 1979).

Statistical analysis of ERP data

At the group level, ERP statistics were evaluated from 0 to 700 ms after the onset of the fifth tone. For each participant, ERPs were averaged for the four combinations of local effects (standard or deviant) and global effects (frequent/global standard or rare/global deviant). The local main effect, global main effect, and their interaction were tested at each electrode and time sample using paired contrasts across participants. To control for multiple comparisons across all electrodes and time samples, p-values were corrected using a max-$|t|$ FWE permutation procedure for paired data (Maris & Oostenveld, 2007; Nichols

& Holmes, 2002). For each permutation, the deviant and standard condition averages were randomly exchanged within each participant, and a new group-level paired-samples *t*-map was computed. The strongest effect observed (maximum absolute *t*-value) anywhere in the electrode-by-time map was used to estimate the chance-level distribution of effects under the null hypothesis. The observed *t*-values were compared against this distribution to obtain FWE-corrected *p*-values. FWE-corrected *p*-values were then evaluated using the predefined threshold criterion. An effect was retained when *p*FWE ≤ .05 was observed in at least five electrodes for at least 20 consecutive samples. Local-global interaction effects were tested with the same group-level paired-samples *t*-test, max-|*t*| FWE correction, and temporal/electrode extent criterion.

Statistical analysis of subjective awareness

Subjective awareness was assessed using the RAS, calculated as the sum of Q1-Q4 for each task (range: 0–4). Participants were classified as showing maximum awareness (RAS = 4/4) or below-maximum awareness (RAS < 4/4). The proportions were compared between the counting and visual interference tasks using a two-sided exact McNemar test (McNemar, 1947), accounting for the paired within-subject design.

Results

Pupil effects in counting and visual interference tasks

Primary pupil analyses focused on the time course of group-level local and global deviance effects within each task. Group-level local and global effects were assessed separately for 26 participants, using paired cluster-based permutation tests across the 0-2000 ms post-stimulus interval relative to the 5th tone.

At the group level, significant pupil effects were observed in the counting task for both local and global contrasts. The local effect extended from 44 to 1232 ms and survived cluster correction (cluster p = 0.0031). Averaged across this significant interval, pupil size was 0.0655 ± 0.0136 *z*-score units for local standards and 0.1646 ± 0.0186 *z*-score units for local deviants, corresponding to a local effect of 0.0991 ± 0.0227 z-score units, $t(25) = 4.37$, $p = 0.00019$, $dz = 0.86$, 95% *CI* [0.0523, 0.1459], *t*max = 6.32 at 498 ms. The global effect extended from 288 to 2000 ms and showed an even stronger response (cluster p = 0.0001). Across this significant interval, pupil size was − 0.0529 ± 0.0125 *z*-score units for global standards and 0.4008 ± 0.0498 *z*-score units for global deviants, corresponding to a global effect of 0.4537 ± 0.0589 z-score units, $t(25) = 7.70$, $p = 4.70 \times 10^{-8}$, $dz = 1.51$, 95% *CI* [0.3323, 0.5750], *t*max = 8.19 at 1006 ms. In both cases, deviants elicited greater pupil dilation than standards. Figure 2 shows the group-average pupil dynamics for both experiments and the corresponding local and global contrasts.

In the visual interference task, both local and global pupil effects were still present at the group level but were weaker than in counting. The local effect extended from 0 to 690 ms and survived cluster correction (cluster p = 0.0247). Averaged across this interval, pupil size was 0.0356 ± 0.0102 *z*-score

units for local standards and 0.0900 ± 0.0107 *z*-score units for local deviants, corresponding to a local effect of 0.0544 ± 0.0135 *z*-score units, $t(25) = 4.04$, $p = 0.00045$, $dz = 0.79$, 95% *CI* [0.0267, 0.0821], *t*max = 4.66 at 482 ms. The global effect extended from 446 to 1818 ms and also survived cluster correction (cluster $p = 0.0083$). Across this interval, pupil size was − 0.0284 ± 0.0100 *z*-score units for global standards and 0.0887 ± 0.0374 *z*-score units for global deviants, corresponding to a global effect of 0.1171 ± 0.0426 *z*-score units, $t(25) = 2.75$, $p = 0.0109$, $dz = 0.54$, 95% *CI* [0.0294, 0.2048], *t*max = 2.88 at 558 ms. Again, both effects reflected greater responses to deviants than to standards. Thus, relative to counting, visual interference reduced the magnitude of both pupil effects.

No significant interaction was observed in counting ($p = 0.065$) or in visual interference ($p = 0.169$). Thus, although local and global pupil effects were present, the magnitude of the local effect did not differ reliably across global contexts under the corrected cluster-level criterion. Supplementary individual-level analyses were broadly consistent with the group-level pattern. Individual pupil effects were more frequent and stronger in counting (73.1% of participants showed global effects) than in visual interference (26.9% showed global effects). A visual summary of individual pupil effects is provided in Supplementary Fig. 2.

Pupil response analyses between experiments showed that, for the local effect, peak latency was later in counting than in visual interference for both local standards (653.00 ± 46.77 ms vs. 396.54 ± 49.11 ms; $p = 0.00045$, $dz = 0.88$) and local deviants (644.77 ± 47.03 ms vs. 431.38 ± 36.52 ms; $p = 0.00651$, $dz = 0.64$), whereas the task × condition interaction for latency was not significant ($p = 0.58862$). For mean pupil size, only pupil responses to local deviants were significantly larger in counting than in visual interference (0.1646 ± 0.0186 vs. 0.0900 ± 0.0107 *z*-score units; $p = 0.00234$, $dz = 0.75$), whereas neither local standards ($p = 0.05784$) nor the task × condition interaction ($p = 0.07926$) was significant. Boxplots of these comparisons are shown in Fig. 3; subject-level values are provided in Supplementary Table 3 for pupil size and Supplementary Table 4 for ERPs.

For the global effect, no between-task differences were observed in peak latency ($p = 1.000$). In contrast, mean pupil size was significantly larger in counting for global deviants (0.4008 ± 0.0498 vs. 0.0887 ± 0.0374 *z*-score units; $p = 0.000083$, $dz = 1.00$). The global deviant-standard effect was also larger in counting (0.4537 ± 0.0589 vs. 0.1171 ± 0.0426 *z*-score units), reflected in a significant task × condition interaction, $F(1,25) = 24.10$, $p = 0.000094$, $\eta p^2 = 0.49$, whereas global standards did not differ significantly ($p = 0.09201$).

Overall, local between-task differences were modest: visual interference was associated with earlier peak latency, whereas amplitude differences were mainly driven by the local deviant response being stronger in the counting task ($p = 0.00234$). At the global level, no significant differences in latency were observed ($F(1, 25) = 0.23$, $p = 0.639$, $\eta p^2 = 0.009$). However, the global pupil effect was stronger during counting than during visual interference ($p = 0.000094$). This was the clearest summary-statistical evidence of task modulation, as reflected by the larger mean pupil response to global deviants ($p = 0.000083$). Consistent with the within-task time-course analyses, deviant sequences generally elicited

larger pupil responses than standard sequences, particularly for the global effect (cluster $p = 0.0001$ in counting and $p = 0.0083$ in visual interference). These results are therefore consistent with the primary pupil analyses showing preserved but attenuated local and global pupil effects under visual interference.

ERP effects in counting and visual interference tasks

Primary EEG analyses were based on participant-level ERPs from all 26 participants, whereas grand-average waveforms were used for visualization. Within each experiment, local, global, and local-by-global interaction effects were tested across participants at each electrode and time sample from 0 to 700 ms. Multiple comparisons were controlled with a maximum $|t|$ permutation-based FWE correction. Significant intervals were retained when corrected pFWE ≤ .05 was observed at a minimum of five electrodes for at least 20 consecutive samples.

At the group scalp level, the counting task showed significant local and global ERP effects. The local effect extended from 220 to 324 ms, and the global effect extended from 196 to 544 ms. The local effect was significant over the posterior electrodes, specifically at Pz, reaching a minimum corrected value of $p = 0.00010$ at 264 ms. Within the significant local window at Pz, mean amplitudes were 0.10 ± 0.18 μV for local standards and 2.61 ± 0.35 μV for local deviants, corresponding to a local effect of 2.51 ± 0.40 μV, $t(25) = 6.32$, $p = 0.0000013$, $dz = 1.24$, 95% *CI* [1.69, 3.33]. For the global effect, significant samples were present at both fronto- and centro-posterior channels, with minimum corrected values of $p = 0.00010$ at 272 ms at Pz and $p = 0.00010$ at 212 ms at Fz. Within the significant global window, mean amplitudes at Pz were 0.27 ± 0.12 μV for global standards and 2.28 ± 0.26 μV for global deviants, corresponding to a global effect of 2.01 ± 0.21 μV, $t(25) = 9.42$, $p = 1.05 \times 10^{-9}$, $dz = 1.85$, 95% *CI* [1.57, 2.45]. At Fz, corrected sample-wise global differences were also present, although the window-averaged contrast was not significant ($p = 0.058$). Furthermore, a significant local-by-global interaction was observed at Pz from 264 to 310 ms (minimum $p = 0.0029$ at 292 ms). The corresponding waveforms and scalp maps indicated an earlier posterior positivity at Pz together with a later frontal negativity at Fz, particularly for the global contrast. Overall, this pattern was consistent with a posterior P300/P3b-like positivity for local effects and a later, more sustained global effect. Furthermore, visual inspection showed an attenuated early fronto-central negativity corresponding in both timing and location to the MMN. Figure 4 shows the group-average ERP waveforms and topographic scalp maps for E1.

In contrast, during visual interference, a short-latency local ERP effect survived the corrected group-level criterion from 38 to 80 ms (minimum $p = 0.00050$ at 46 ms), whereas no global ERP effect survived correction. The local effect was significant at Fz (minimum $p = 0.00330$ at 44 ms) but not at Pz. Within this interval at Fz, mean amplitudes were − 0.73 ± 0.15 μV for local standards and − 1.87 ± 0.22 μV for local deviants, corresponding to a local effect of -1.14 ± 0.21 μV, $t(25) = -5.48$, $p = 0.000011$, $dz = -1.07$, 95% *CI* [-1.57, -0.71]. Thus, relative to counting, visual interference strongly attenuated the later ERP effects; only an early frontal local effect remained, whereas the sustained global effect was absent. Overall, these findings indicate robust local and global EEG effects during counting, but a markedly reduced group-level pattern during visual interference. Figure 5 shows the group-average ERP waveforms and topographic scalp maps for E2. Consistent with the group-level pattern, individual ERP effects were

more frequent in counting (all participants showed at least one qualifying global-effect interval) than in visual interference (53.8% showed global effects). A visual summary of individual ERP effects is provided in Supplementary Fig. 3. A summary of the main group-level statistics for both pupil and ERP results across experiments can be found in Supplementary Table 5.

Behavioral awareness results

Behavioral awareness was higher during counting than during visual interference. Maximum awareness (RAS = 4/4) was observed in 88.5% of participants (23/26) during counting and in 61.5% of participants (16/26) during visual interference. Fifteen participants maintained maximum awareness across both tasks, eight changed from maximum to below-maximum awareness, one showed the opposite change, and two remained below maximum. The reduction in the proportion of participants attaining maximum awareness was significant according to a two-sided exact McNemar test ($p = 0.0391$). Participant-level transitions in regularity awareness between tasks are shown in Fig. 6. Descriptively, the largest reduction was observed for Q4, which assessed awareness of global deviance. Individual awareness responses and perceived deviant-trial estimates are provided in Supplementary Table 6.

Discussion

The present study investigated whether local and global auditory regularity violations can be detected through two complementary psychophysiological measures, pupil dynamics and EEG, and whether these effects are modulated by visual interference. Given that ERPs provide a temporally precise measure of cortical electrical activity (Luck, 2014; Nunez & Srinivasan, 2006), whereas pupil responses are indirect markers of arousal-related neuromodulatory subcortical activity (Alnæs et al., 2014; Joshi & Gold, 2020; Mazancieux et al., 2023; Murphy et al., 2014), the combination of both measures helps distinguish different levels of deviance processing (higher-order global and lower-order local processing). The main finding was that pupil responses showed reliable local and global effects not only during active counting, but also during visual interference, although both effects were attenuated in the visual-interference condition. In contrast, ERP effects were significant during active counting. However, only a short-latency local effect survived during visual interference, whereas the later global effects did not survive the corrected group-level criterion. Together, these findings suggest a dissociation between pupil-linked arousal responses and ERP markers of auditory regularity processing: whereas ERP cortical responses appear strongly dependent on attentional availability, subcortical pupil responses indicate that auditory deviants can still evoke physiological responses under divided or redirected attention.

The pupil findings replicate and extend previous work showing that deviant stimuli in the local-global paradigm elicit pupil dilation (Liao et al., 2016; Mazancieux et al., 2023; Quirins et al., 2018; Sangaré et al., 2023). During active counting, both local and global deviants produced larger pupil responses than standards, consistent with the idea that behaviorally relevant deviations recruit arousal-related neuromodulatory systems. This is in line with Mazancieux et al. (2023), who showed that global deviants elicit responses in pupil size, the locus coeruleus, and other subcortical neuromodulatory structures.

Importantly, in the present study these pupil effects were not abolished by visual interference. This suggests that pupil dilation may capture a relatively robust physiological response to deviance or salience, even when auditory processing is weakened by a competing visual task (Bekinschtein et al., 2009; Quirins et al., 2018). However, the reduced effect size during visual interference indicates that pupil responses are not completely automatic or independent of task context, but likely reflect the interaction between deviance detection, attentional allocation, and arousal regulation (Aston-Jones & Cohen, 2005; Joshi & Gold, 2020; Polich, 2007).

The persistence of pupil effects during visual interference is particularly relevant because EEG effects were strongly attenuated during the same task. Bekinschtein et al. (2009) proposed that local effects reflect early auditory change detection, whereas global effects reflect higher-order integration across trials and are closely linked to awareness of the global regularity. In their study, the global ERP effect disappeared when participants were distracted by a visual task, supporting its interpretation as a marker of conscious access rather than mere vigilance. The present EEG results are broadly consistent with this framework: local and global ERP effects were observed during active counting, whereas group-level ERP effects were mostly absent during visual interference. Thus, the visual task appears to have reduced cortical processing of auditory regularities, particularly the later P300/P3b-like activity associated with context updating. Nevertheless, conscious processing cannot be fully explained within this framework alone (Naccache et al., 2015; Nourski et al., 2021; Perez et al., 2021). In the present study, global-deviance responses were still observed in pupil size during visual interference. These results suggest that global effects may be expressed differently across physiological measures, as pupil and ERP responses to deviance can show limited overlap (de Gee et al., 2021; Hong et al., 2014; Kamp & Donchin, 2015; LoTemplio et al., 2021).

In the present study, we found a similar pattern to previous local-global paradigm studies (e.g., Bekinschtein et al., 2009), with a less pronounced early mismatch negativity (MMN) for local violations, and a later posterior positivity (P300/P3b) for global violations. The MMN indexes automatic auditory change detection and regularity updating but is sensitive to attention and stimulus timing (Näätänen et al., 2007, 2011; Winkler et al., 1996). One possible explanation for the attenuated MMN observed here is the temporal structure of the task. According to the adaptation account proposed by May and Tiitinen (2010), the MMN may be understood as an amplitude- and latency-modulated expression of the auditory N100 response. Repeated standards adapt the neuronal populations responding to them, whereas deviants activate less-adapted or “fresh” afferent populations. From this perspective, the size of the deviant-minus-standard response depends on the temporal dynamics of adaptation and recovery. With longer intervals between tones, responses to repeated standards may recover more before the next stimulus occurs, reducing the difference between standard and deviant responses. This could attenuate an MMN-like effect even if auditory deviance is still detected at later processing stages. Therefore, the timing of the present paradigm may have diminished the observable MMN ERP response. The finding that the global effect also appeared as a later P300/P3b-like component is consistent with the view that global violations require integration across trials and updating of a higher-order regularity representation (Bekinschtein et al., 2009; El Karoui et al., 2015; Wacongne et al., 2011). The stronger attenuation of ERP

effects during visual interference is consistent with the well-established sensitivity of P300/P3b activity to attention, task relevance, and processing demands (De Vos & Debener, 2014; Kok, 2001; Polich, 2007). In the visual-interference condition, attentional resources were prioritized toward visual target detection, while the auditory sequences were task-irrelevant. Dual-task studies indicate that P300 amplitude is distributed reciprocally across concurrent tasks, such that greater resource allocation to one task is accompanied by reduced P300 responses to events in the competing task (Nash & Fernandez, 1996; Wickens et al., 1983). Consistently, hierarchical auditory studies have shown that later P300/P3b responses to higher-order regularity violations depend strongly on attentional engagement and are reduced or absent when attention is directed away from the auditory stream (Chennu et al., 2013; Kompus et al., 2020). Thus, the absence of corrected P300 effects during visual interference may reflect reduced engagement of task-dependent cortical processes involved in context updating, rather than a complete absence of auditory deviance processing.

The dissociation between pupil and EEG responses is an important contribution of the present study. Pupil responses remained significant under visual interference, whereas corrected ERP effects mostly did not. This pattern suggests that auditory deviants can engage arousal-related neuromodulatory systems in the absence of clear cortical ERP signatures. Moreover, the absence of a significant local-by-global interaction in pupil responses suggests that effects were not strongly dependent on whether deviance was defined at the local or global level. This is consistent with Mazancieux et al. (2023), who reported similar pupil responses and LC activation for global deviance detection, while local deviance was more evident in auditory cortical regions. Thus, pupil dilation may reflect a broader subcortical arousal response to unexpected or behaviorally relevant stimuli, rather than a highly specific response to the precise type of cortical auditory regularity violation. However, this interpretation should be treated with caution. Pupil size is only an indirect marker of LC-NE activity and is not solely specific to the locus coeruleus. Pupil dilation can also reflect other neuromodulatory systems (Joshi & Gold, 2020; Reimer et al., 2016), sensory-orienting responses (Sara & Bouret, 2012), visual task demands (Mathôt, 2018; Pan et al., 2022), cognitive effort (Beatty, 1982; Kahneman & Beatty, 1966; van der Wel & van Steenbergen, 2018), and changes in attentional state (Alnæs et al., 2014; Strauch et al., 2022). Therefore, the present results should not be interpreted as direct evidence of unaware LC-NE system processes of global deviants. Instead, pupil-linked arousal responses (an indirect index of subcortical neuromodulatory processes) remained sensitive to auditory regularity violations under visual interference, whereas cortical scalp EEG markers of deviance processing were attenuated. Thus, the present findings suggest that cortical and subcortical responses may reflect different levels of the deviance-processing hierarchy: MMN and P300/P3b activity appear more sensitive to the specific cognitive and attentional requirements of the local-global structure, whereas pupil responses may index a broader arousal response to unexpected or behaviorally relevant stimuli.

Limitations

This study has some limitations. First, the present paradigm differed from the original local-global EEG study in stimulation timing, number of sessions, and task structure. These differences may have reduced

the signal-to-noise ratio of the EEG effects and may partly explain an attenuated MMN component in the present study (Bekinschtein et al., 2009; May & Tiitinen, 2010; Polich, 2007). Importantly, the marked attenuation of later ERP component effects during visual interference should not be interpreted as evidence that cortical processing had completely vanished. The grand-average topographies and individual-level analyses suggest that weak local and global ERP responses may still have been present in some participants, but were likely too strongly attenuated or variable to survive conservative multiple-comparison correction, as shown in previous studies (Maris & Oostenveld, 2007; Sassenhagen & Draschkow, 2019).

Second, the visual interference condition primarily manipulated divided attention rather than serving as a pure assessment of automatic auditory processing (Bekinschtein et al., 2009; Naccache et al., 2015). This condition alters attentional allocation, motor demands, and overall arousal, with visual stimulation potentially affecting pupil dynamics despite luminance controls (Mathôt, 2018; Mathôt & Ivanov, 2019; Pan et al., 2022). Consequently, distinguishing reduced auditory processing from visual task demands becomes complex (van der Wel & van Steenbergen, 2018; Zekveld et al., 2018). Furthermore, the counting condition consistently preceded the visual interference condition. Although counterbalancing could have clarified task and order effects, design features such as habituation phases, randomized trials, and a shortened paradigm mitigate concerns that attenuation was driven by order. Increased familiarity with auditory regularities should facilitate, rather than attenuate, deviance-related responses (Jacobsen et al., 2005; Southwell & Chait, 2018). Thus, while order-related effects cannot be entirely excluded, they likely do not account for the reduced pupil and ERP effects observed during visual interference.

Third, the sample consisted of healthy young adults, and the study did not include direct measures of subcortical activity, such as fMRI measurements. Therefore, the findings should not be taken as direct evidence of isolated LC-NE activity for local and global regularity processing. A more conservative interpretation is that pupil-linked arousal responses remained sensitive to auditory deviance under visual interference, similar to what has been reported previously (Mazancieux et al., 2023; Quirins et al., 2018; Sangaré et al., 2023). Future studies using direct measures of subcortical activity and more direct assessments of awareness are needed to clarify the neural sources and cognitive significance of these dissociated pupil and EEG responses.

Conclusion

The present study supports the use of combined EEG-pupillometry measurements to study local and global auditory deviance processing in healthy adults. These results suggest that local and global auditory deviants elicit robust pupil responses during active counting and weaker but still significant pupil responses during visual interference. In contrast, EEG markers of local and global deviance were clearly present during active counting but were attenuated during visual interference. This pattern shows differential sensitivity across brain measurement modalities: MMN and P300/P3b responses associated

with local-global processing appear to depend strongly on attentional engagement, whereas pupil dynamics may provide a more sensitive index of deviance-related processing under reduced attention.

Importantly, while ERP components and pupil dynamics may serve as indicators of implicit LC-NE system activity, these findings do not constitute direct subcortical measurements. Instead, the evidence indicates that brain systems associated with pupil response, such as neuromodulatory or arousal-related networks, can remain responsive to auditory regularity violations, even when most ERP effects are absent. Together, these findings illustrate the complexity of interactions between cortical ERP activity and pupil-linked arousal systems.

Overall, the results support the value of multimodal EEG-pupillometry approaches for studying hierarchical auditory processing and its underlying cognitive processes, and provide a basis for future work examining how cortical and subcortical LC-NE-related markers contribute to awareness and attention-dependent deviance detection.

Declarations

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Ethics statement

The experiment was conducted according to the tenets of the Declaration of Helsinki with the review and approval of the Medical Ethics Committee of the University of Oldenburg (approval number: Drs/EK2025/160-01), Oldenburg, Germany. The study was conducted in accordance with the local legislation and institutional requirements. Participants provided written informed consent to participate in the study.

Author Contributions

MCA: Conceptualization, Data acquisition and curation, Formal analysis, Investigation, Methodology, Project administration, Visualization, Writing – original draft. SD: Methodology, Supervision, Writing – review & editing. KW: Conceptualization, Funding acquisition, Methodology, Resources, Supervision, Writing – original draft.

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Competing interests

The authors declare no competing interests.

Data Availability Statement

The data supporting this study will be deposited in https://openneuro.org/ or suggested repository. The DOI/accession will be added after acceptation. Data are available to editors and reviewers from the corresponding author upon request.

Code availability

The MATLAB code is publicly available on GitHub (https://github.com/micufx/Pupillometry-EEG).

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Figures

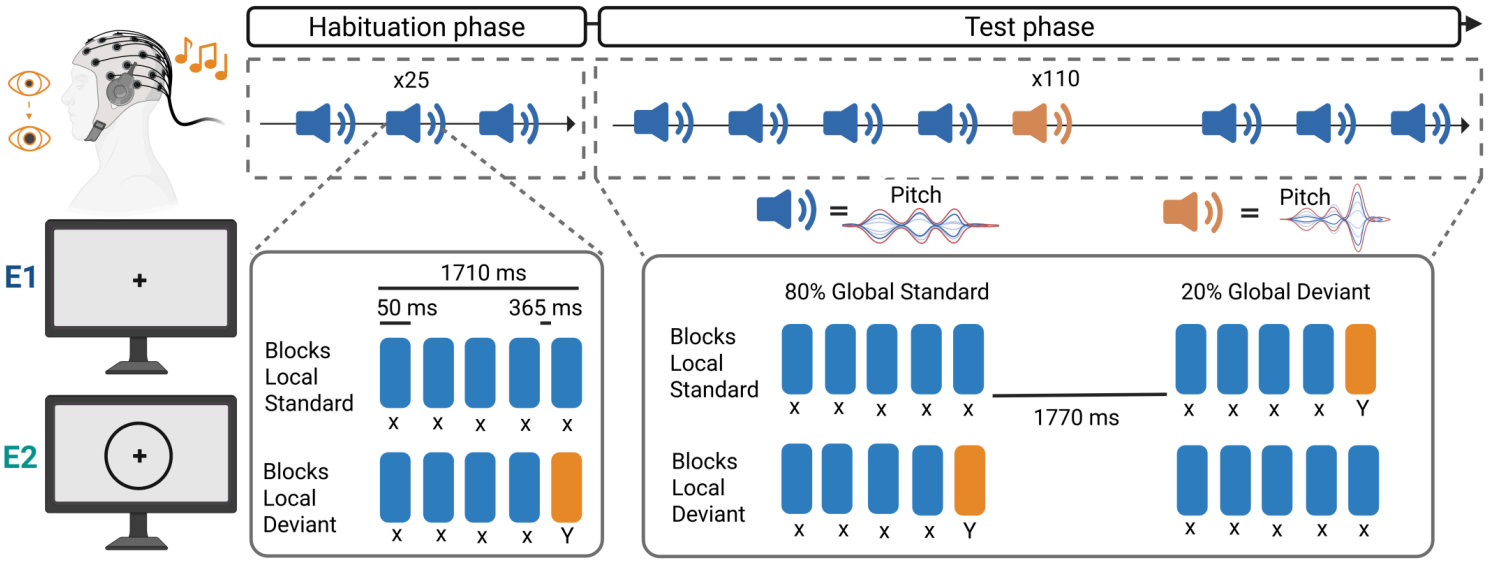


Figure 1

Experimental design and local-global auditory paradigm structure. Schematic overview of the two within-subject experiments. In Experiment 1 (E1; counting), participants gazed at a fixation cross and silently counted deviant auditory events. In Experiment 2 (E2; visual interference), the same auditory sequences were presented while the participants performed a visual target-detection task. Each auditory trial consisted of five tones. Local standard sequences contained five identical tones (xxxxx; blue), whereas local deviantsequences contained four identical tones followed by a pitch change (xxxxY; orange). Each block began with a habituation phase in which only one sequence type was presented, followed by a test phase in which the habituated sequence occurred frequently (global standard, 80%) and the alternative sequence occurred infrequently (global deviant, 20%). The probability structure was reversed across the different block types. Figure adapted from Mazancieux et al. (2023).

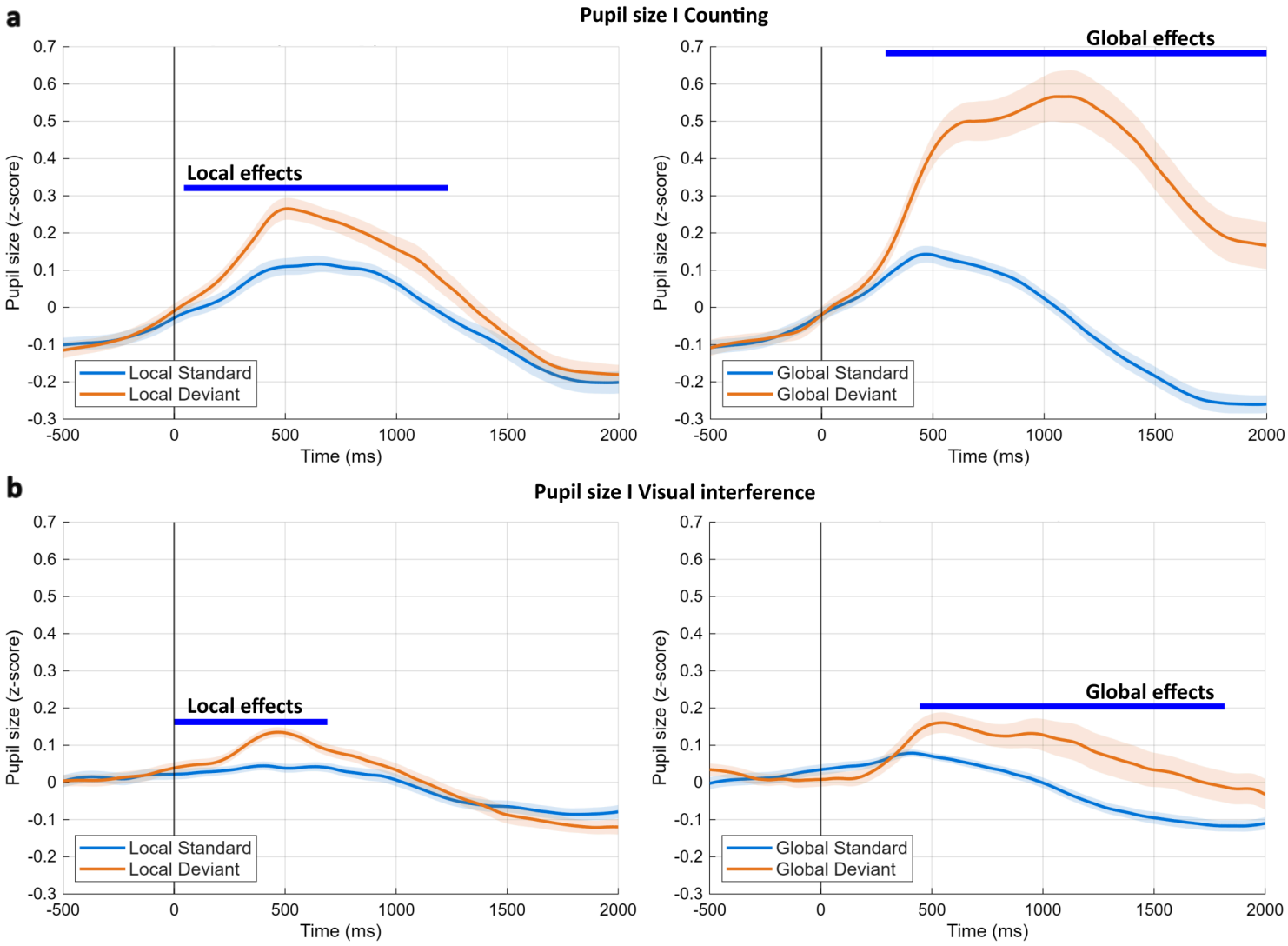


Figure 2

Group-level pupil responses to local and global deviance in both the active counting and visual interference tasks. Grand-average *z*-scored pupil response time-locked to the onset of the fifth tone (vertical grey line; 0 ms). Panel **(a)** shows the counting task,and panel **(b)** shows the visual interference task. The left panels show local effects (local standard vs. local deviant), and the right panels show global effects (global standard vs. global deviant). The lines represent the condition means across participants, and the shaded areas represent ± one standard error of the mean (*SEM*). Blue horizontal bars indicate significant time intervals in which deviant and standard responses differed after cluster-based family-wise error correction (*p*FWE ≤ .05). Deviant sequences elicited larger pupil dilation than standard sequences in both tasks, although the effects were attenuated during visual interference.

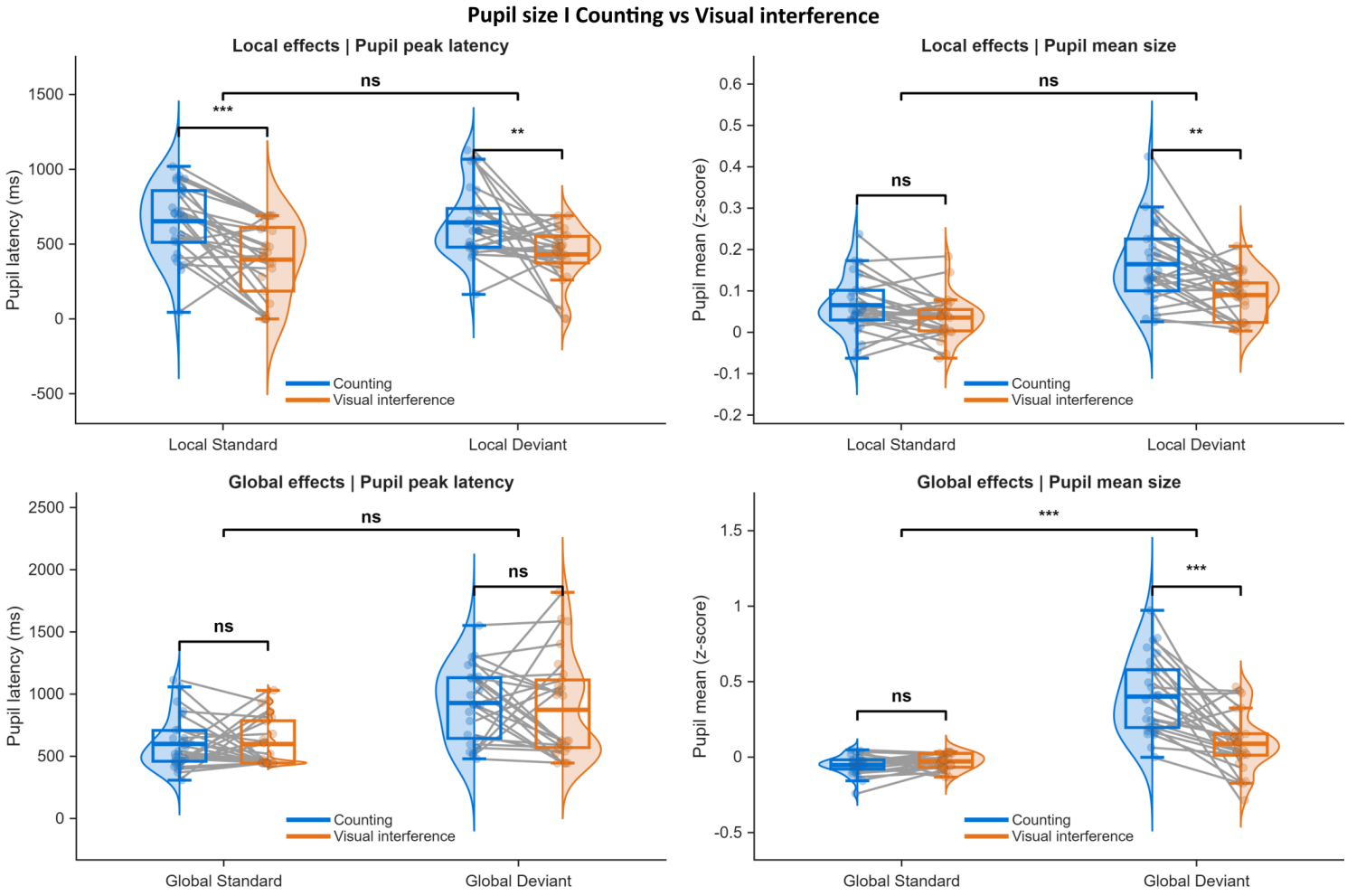


Figure 3

Between-task comparison (active counting task vs. visual interference) of pupil peak latency and mean pupil response. Subject-level pupil peak latencies and mean *z*-scored pupil responses were extracted from the significant group-level time windows and compared between the counting and visual interference conditions. The toppanels show the local effects, and the bottom panels show the global effects. The left panels show the peak latency, and the right panels show the mean pupil size. Blue distributions indicate counting, and orange distributions indicate visual interference. Boxes show the interquartile range and central tendency, individual points represent participants, and gray lines connect paired observations from the same participant across tasks. For each effect and measure, a 2 × 2 repeated-measures ANOVA was performed with the factors task and condition. Short brackets indicate Holm-adjusted paired comparisons between tasks for standard and deviant responses separately, whereas the long bracket indicates the Holm-adjusted task × condition interaction; ns = non-significant, * $p \leq .05$, ** $p \leq .01$, *** $p \leq .001$.

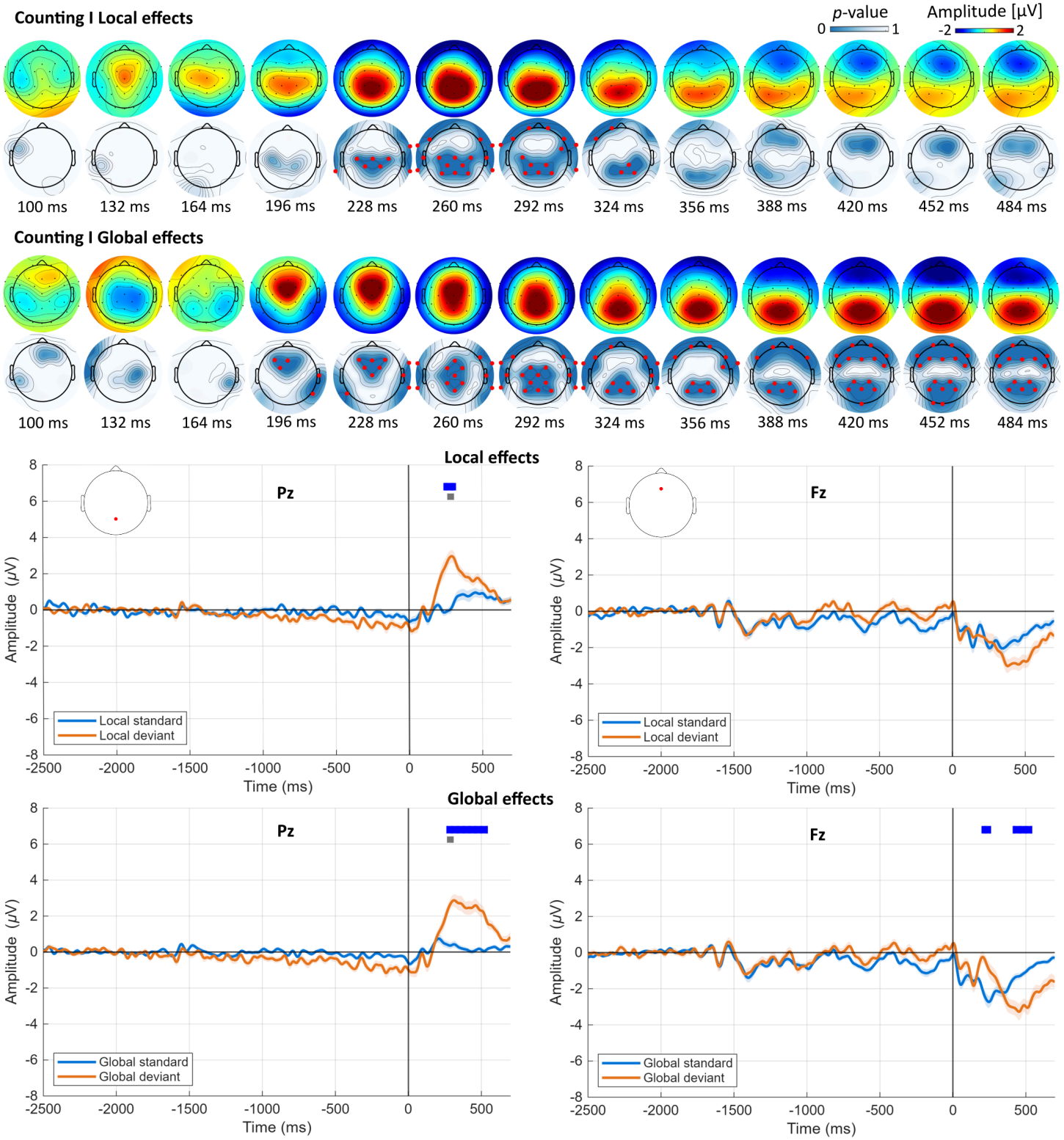


Figure 4

Group-level Event-Related Potential (ERP) responses and scalp distributions in the countingtask. Local and global ERP effects are shown for the counting task, time-locked to the onset of the fifth tone (vertical grey line; 0 ms). For each contrast, the upper rows show the scalp distributions of the grand-average ERP amplitudes at selected post-stimulus time points, and the lower rows show the corresponding corrected *p*-value maps. Red dots mark electrodes contributing to significant corrected

effects (extent criterion: corrected *p*FWE ≤ .05, at least fiveelectrodes for at least 20 consecutive samples). The lower panels show the ERP waveforms at Pz and Fz for local effects (local standard vs. local deviant) and global effects (global standard vs. global deviant). The lines show the group-mean condition responses, and the shaded areas represent the standard error of the mean (*SEM*). Blue horizontal bars indicate channel-specific corrected samples within significant whole-scalp local or global effect windows after max-|t| permutation-based family-wise error correction and the predefined temporal/electrode extent criterion. Grey bars indicate channel-specific corrected samples of the local-by-global interaction within its significant whole-scalp window. In the counting task, both local and global ERP effects survived correction, with prominent late posterior positivity at Pz.

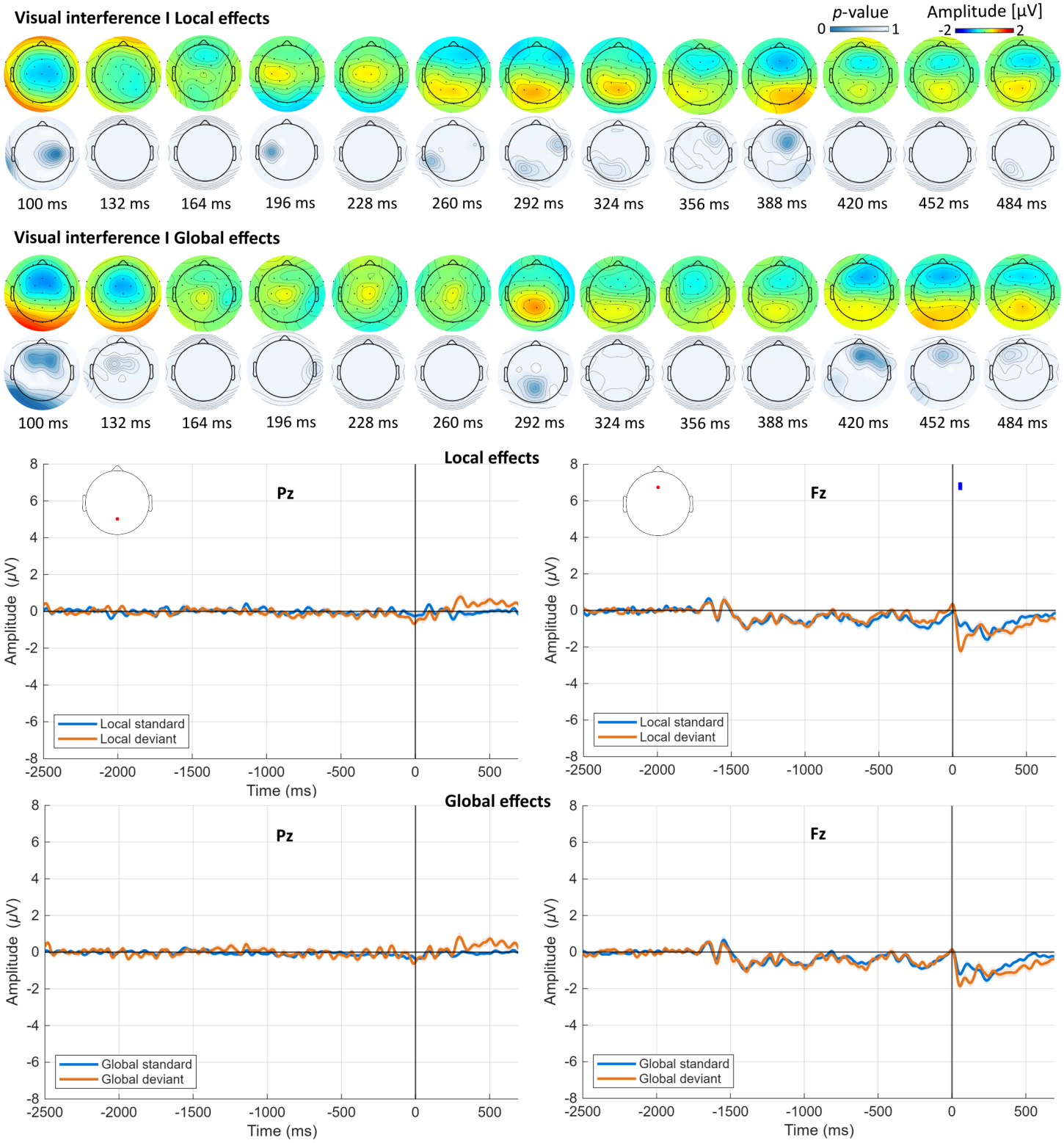


Figure 5

Group-level Event-Related Potential (ERP) responses and scalp distributions in the visual interference task. Local and global ERP effects are shown for the visual interference task, time-locked to the onset of the fifth tone (vertical grey line; 0 ms). For each contrast, the upper rows show scalp distributions of grand-average ERP amplitudes at selected post-stimulus time points, and the lower rows show the corresponding corrected *p*-value maps (extent criterion: corrected *p*FWE ≤ .05, at least five electrodes for

at least 20 consecutive samples (40 ms)). The lower panels show the ERP waveforms at Pz and Fz for local effects (local standard vs. local deviant) and global effects (global standard vs. global deviant). The lines represent the group-mean condition responses across participants, and the shaded areas represent the standard error of the mean (*SEM*). The blue bar shows a short-latency local ERP effect that survived correction from 38 to 80 ms, with significant samples at Fz, whereas no global ERP effect survived the corrected group-level criterion. Later deviance-related effects remained strongly attenuated.

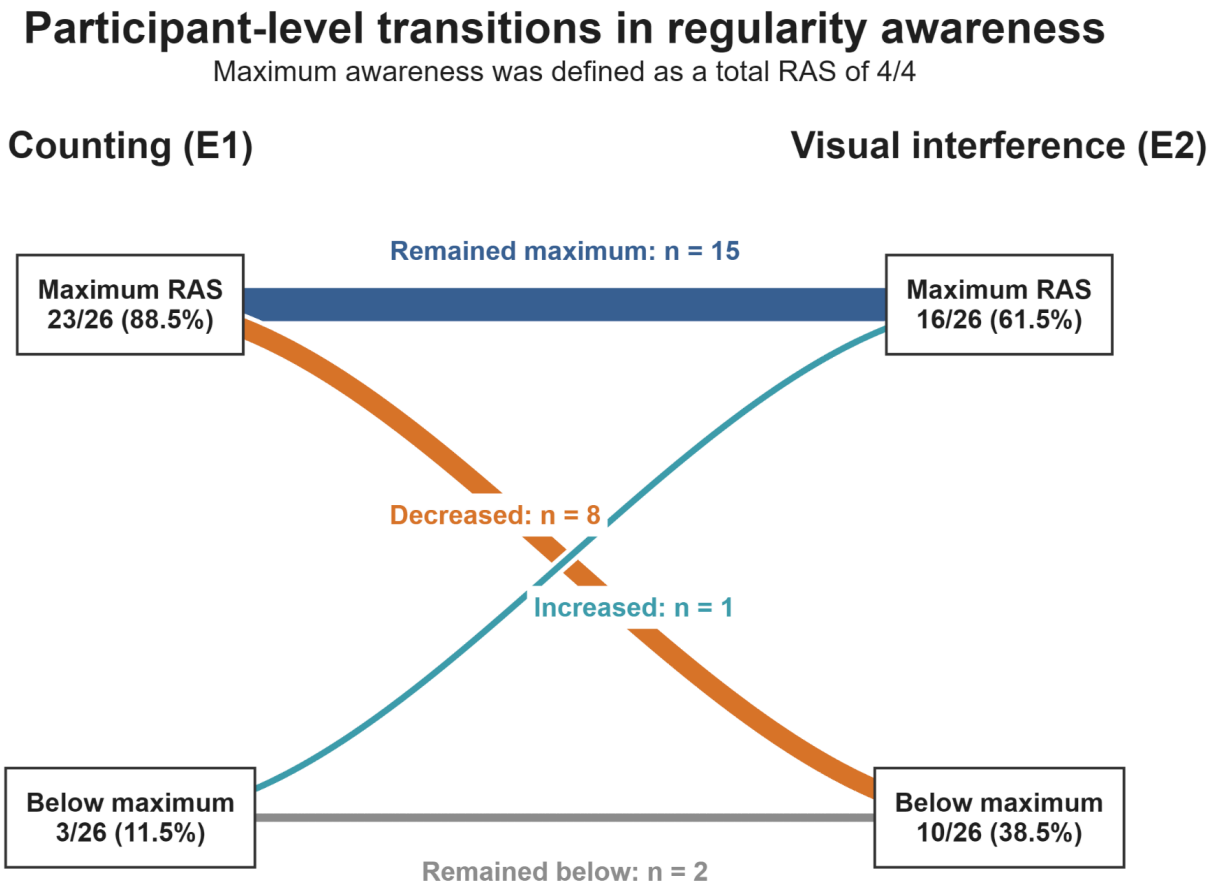


Figure 6

Participant-level transitions in regularity awareness between the counting and visual interference tasks. Maximum awareness was defined as a total Regularity Awareness Score (RAS) of 4/4, whereas scores below 4 were classified as below-maximum awareness. Boxes show the number and percentage of participants in each category, and connecting-line widths are proportional to the number of participants following each transition. Fifteen participants maintained maximum awareness, eight changed from maximum to below-maximum awareness, one showed the opposite change, and two remained below maximum. The proportion attaining maximum awareness decreased from 88.5% during counting to 61.5% during visual interference (two-sided exact McNemar test, $p = 0.0391$).

Supplementary Files

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