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ORIGINAL ARTICLE

Unconscious Fear Requires Attention to Distort Vision in Safe Context

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Abstract Despite widespread exposure to stress and threats, why some develop anxiety while others do not remains unclear. We hypothesize that this discrepancy links to unconscious fear memory generalization in safe contexts, a poorly understood area. Here, we tested whether such memories unconsciously bias visual processing and if attention-based control suppresses this effect. Visual orientations paired with threat (in a threatening context) were rendered invisible via fast chromatic flicker above critical flicker-fusion frequency (CFF), then presented in a safe context. Experiment 1 (attended orientation discrimination task) and Experiment 2 (attended duration discrimination task vs. unattended central color detection task) were conducted. EEG revealed significant unconscious fear responses (CS+ vs. CS−) in attended conditions, positively correlated with broad-alpha power (replicated across experiments). No significant responses emerged for unattended stimuli, despite elevated alpha. These findings show unconscious fear distorts visual processing during generalization in a safe context, with top-down attention gating this effect via broad alpha oscillations—prioritizing it when attended and suppressing it when unattended.

Keywords Unconscious fear · Top-down attention · Alpha oscillations · Visual processing · Signal-to-noise ratio

Introduction

Fear plays a critical role in human environmental adaptation and survival [1, 2]. While everyone encounters stress and fear in daily life, a key unresolved puzzle is as follows: after a threatening event ends and the context becomes safe, why do some individuals adapt smoothly, while others develop anxiety disorders such as post-traumatic stress disorder (PTSD)? A well-established finding is that fear-related memories do not vanish with the removal of imminent threats [3]. Instead, they persist in the brain, residing both in the classical emotional processing network [4] and the primary sensory cortex [5], which supports precise, rapid threat evaluation [6]. Many of these persistent fear memories operate outside conscious awareness, and their abnormal expression in safe contexts is widely hypothesized to contribute to maladaptive fear responses in anxiety disorders [7, 8].

At the heart of this puzzle lie two interconnected, understudied questions that drive the current work: first, in safe contexts, do these persistent, unconscious fear memories actively influence sensory and perceptual processes Second, what mechanisms does the brain use to regulate these memories and prevent their maladaptive expression A leading view posits that unconscious fear memories in safety engage in a competitive interplay with newly formed safety memories [9, 10]—with the balance between the two shaping adaptive or maladaptive outcomes [11].

Traditional therapies like cognitive-behavioral therapy [12] and exposure therapy [13, 14] aim to strengthen safety memories via repeated conscious exposure to previous fear

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cues in a safe context, leveraging this competitive dynamic to counteract unconscious threat memories. However, conscious exposure is often accompanied by intense unpleasantness and distress, leading to high dropout rates and limiting its clinical utility [15]. In contrast, unconscious exposure paradigms [16–18]—targeting fear memories without conscious awareness of cues—have emerged as a promising alternative: meta-analytic evidence and clinical work [16, 17, 19] confirm their efficacy in re-editing fear memories and reducing symptoms, all while avoiding explicit distress. These findings strongly suggest that unconscious fear memories are not unregulated; instead, they are governed by intrinsic neural mechanisms that can be targeted therapeutically—highlighting the urgent need to uncover effects and regulation mechanisms of unconscious fear in safe contexts, so as to refine and enhance such interventions.

Regarding the effects of unconscious fear, indirect clues from prior research [5, 6] hint at potential mechanisms (e.g., fast and precise neural plasticity [6]) but fall short of direct answers. For example, a primate study [5] established fear associations between visual orientations and threats using supraliminal gratings. When these orientations were later masked to subliminal levels, fear cues enhanced V1 neuron firing rates—indicating consciousness-independent shaping of the primary visual system. However, this primate study was confined to threatening contexts, leaving open whether newly acquired fear cues can still unconsciously modulate basic perception in safety. Regarding this issue, the present study provides direct neural evidence in the human brain illustrating such unconscious fear-induced effects in safe contexts.

Regarding regulation, top-down attention has been proposed as a potent modulator of supraliminal threat processing (e.g., supraliminal fearful faces), which comprises both initial fast subcortical unconscious fear [20] and subsequent slow cortical conscious fear responses [21, 22]. A classic fMRI study shows that the amygdala's ability to discriminate supraliminal emotional stimuli is entirely attention-dependent—when attention was diverted to distractors, emotional discrimination was abolished [23]. However, limitations of this fMRI study are twofold: first, amygdala activation under unattended conditions was substantially reduced, far below the level observed under attended conditions; second, the fMRI signal lacks temporal dynamic information. Two EEG studies with higher temporal resolution [24, 25] provided more dynamic details, revealing that inattention primarily attenuated late attention-related and consciousness-related components, without clearly dissociating emotion's modulatory effect on early visual activity. Thus, it remains unclear whether top-down attention governs the ability of unconscious fear to distort visual processing in safe contexts—a key candidate mechanism for how the brain manages unconscious fear.

To address these gaps, we conducted two human EEG experiments in healthy participants. Our primary goals were to: (1) test whether newly learned fear unconsciously modulates visual processing in safe contexts; and (2) clarify whether and how this effect is regulated by top-down attention. Elucidating these mechanisms is critical for advancing our understanding of the functional role of unconscious fear and its intrinsic regulatory mechanisms—knowledge that can inform the refinement of therapies targeting unconscious fear. On this point, notably, sustained alpha-band activity is proposed as a general mechanism regulating unconscious processes (suppressing noise and enhancing signal) during the early period before conscious access to stored knowledge is achieved [26] (see Discussion for more information). If attention modulates unconscious fear, the relationship between alpha-band activity and unconscious fear thus merits further investigation. With direct implications for anxiety disorder research and treatment, this work fills a key gap in understanding how unconscious fear operates and is controlled during generalization in safe contexts.

Materials and Methods

Procedures and protocols of this study adhered to the tenets of the Declaration of Helsinki and were approved by the Ethics Review Board of the Institute of Psychology, Chinese Academy of Sciences. All participants were recruited through the institute's participant recruitment platform, had normal or corrected-to-normal visual acuity, provided prior written informed consent, and were naive to the study's purpose before participation. Data supporting the findings of this study are available from the corresponding author upon reasonable request.

Participants

A total of 39 college students (25 females, 14 males; all right-handed; age range: 18–26 years) participated in the study. Sixteen participants (11 females) took part in Experiment 1, with one participant's data excluded due to excessively above-chance performance in the 2-AFC orientation discrimination test—reliably exceeding the 50% chance level (77.5% and 70% in Sessions 1 and 2, corresponding to P = 0.0002 and P = 0.005, respectively, if tested against a binomial distribution, 40 trials per session). Twenty-three participants (14 females) participated in Experiment 2, and data from all participants were included in the formal analyses.

Apparatus and Stimuli

Visual stimuli were presented on a CRT monitor (refresh rate = 75 Hz, resolution = 1024 × 768 pixels, viewing

distance = 60 cm). Gamma-correction was performed for this CRT monitor to render its output brightness linearly changing with the input RGB parameters. All visual stimuli were generated using MATLAB (The MathWorks, Natick, MA, USA) with the Psychophysics Toolbox extensions [27, 28]. The unconditioned stimulus (US) consisted of aversive electrical shocks (90 ms duration; 67 pulses/s), produced by a constant-current STM200 stimulator (BIOPAC Systems, Inc., Goleta, CA, USA) and triggered via MATLAB functions. Two stimulating electrodes were attached side-by-side to the dorsal carpal region of the left wrist to deliver the shocks. US intensity was individually calibrated in advance to achieve a subjective pain rating of 70% (7–8 on a 0–10 scale, where 0 = no pain and 10 = extreme pain).

During the fear conditioning (including top-up) phases, the conditioned stimuli (CSs) were explicitly visible in both experiments (Fig. 1 and Fig. S3). In Experiment 1, grayscale luminance gratings were used—tilted either clockwise or counterclockwise from vertical (visual angle = 3.5°)—with spatial frequency, spatial phase, and luminance contrast varied across trials. This design ensured that aversive shocks (US) were paired with visual orientation rather than other visual features. To minimize visibility artifacts from small eye movements, all gratings were presented against a chromatic noise square (visual angle = 11.4°) surrounded by a gray background.

In Experiment 2, given that stimuli were presented in the peripheral (rather than central) visual field during the main

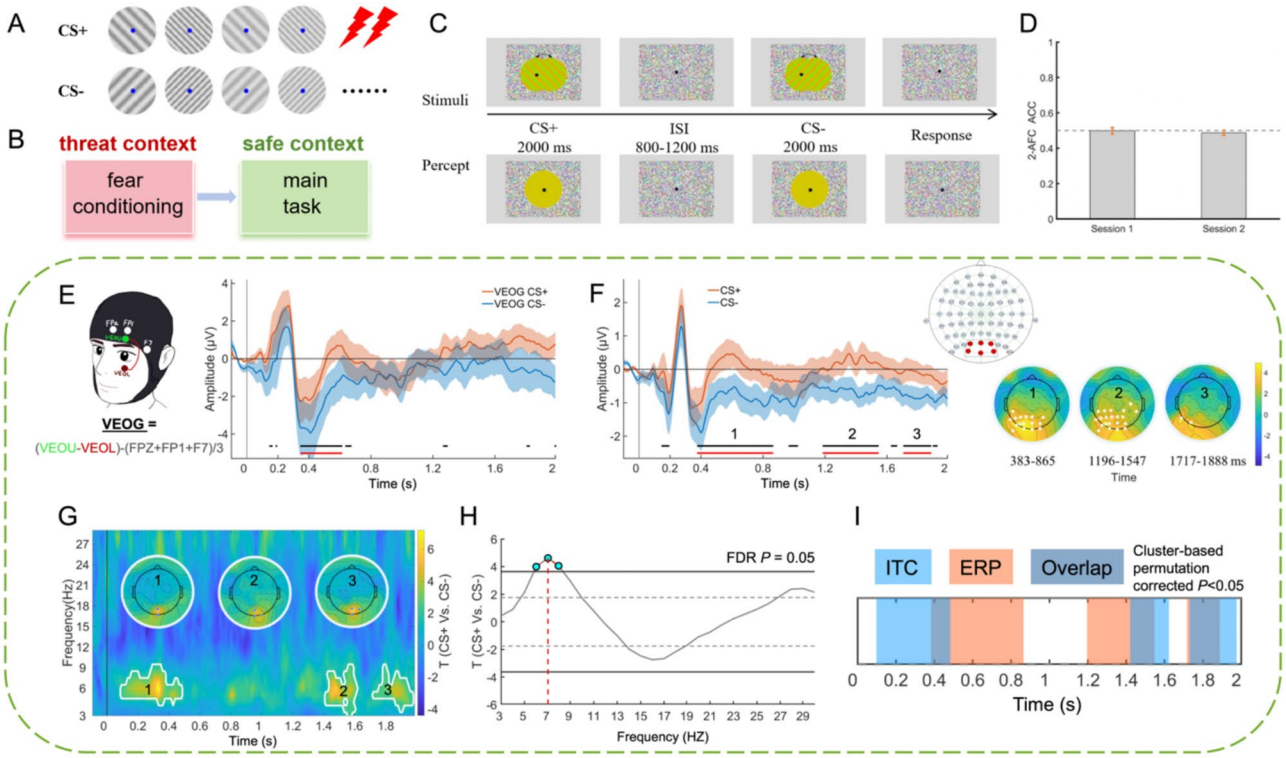


Fig. 1 Experimental design and neurophysiological results of Experiment 1, demonstrating that pre-learned fear enhances visual processing unconsciously in a safe context. **A** Stimuli employed and aversive shock associations established during the fear-conditioning phase. **B** The subsequent main experimental task was administered in a context devoid of aversive threat (i.e., a safe context). **C** Schematic overview of the main task procedure. Participants completed a 2-alternative forced choice (2-AFC) judgment to identify which flicker was oriented clockwise (or counterclockwise), despite consciously perceiving the stimuli as uniform, static yellow disks. **D** Behavioral accuracy (ACC) of the 2-AFC task across experimental sessions. The dotted horizontal line denotes the chance-level performance (ACC = 0.5), and error bars represent the standard error of the mean (SEM). **E** As a neurophysiological marker of unconscious fear processing, vertical electrooculography (VEOG) signals were recorded via bipolar electrodes positioned above (VEOU) and below (VEOL) the left eye; the mean signal from three adjacent frontal electrodes was subtracted to control for volume conduction artifacts. For panels **E** and **F**, black dots indicate uncorrected $P < 0.05$, while red dots denote cluster-based permutation-test corrected $P < 0.05$. Shaded areas around each curve represent ±SEM. **F** Event-related potential (ERP) analysis (left panel) of the occipital region of interest (ROI; upper-middle panel) identified three clusters of unconscious fear-responsive activity, which were spatially distributed across occipitoparietal regions (right panel). **G** Inter-trial coherence (ITC) analysis further detected three clusters of oscillatory synchronization, predominantly localized to the occipital midline. Cluster-based permutation test was used to correct for multiple comparisons. **H** These three ITC clusters exhibited peak synchronization at 7 Hz in the frequency domain. **I** Time-domain topography of the ITC clusters partially overlapped with the clusters of differential ERP activity linked to unconscious fear processing.

task (resulting in reduced perceptual resolution for visual features), chromatic gratings with no variations in spatial frequency, phase, and contrast were employed during both the fear conditioning phase and the subsequent main task. By holding all other confounding features invariant, this design was to maximize the representation of visual orientations, so as to strengthen the association between predefined visual orientation and aversive shocks. The same chromatic gratings were used in the main task, with the key modification that each grating alternated rapidly with its anti-phase counterpart (exceeding the critical flicker-flicker frequency, CFF) to achieve complete perceptual fusion into a static yellow disk [29, 30]. Since Experiment 2 involved color change (from white to red) of the central fixation, the chromatic noise square used in Experiment 1 was replaced by a uniform gray background to allow immediate detection of color change.

For the chromatic gratings in the main task, the blue channel intensity was fixed at 0. Red and green channel intensities varied according to two out-of-phase sinusoidal functions (spatial frequency = 5 cycles per degree; red mean = 134, green mean = 151; red range = 80, green range = adaptively adjusted; phase lag = 180°). The gratings' orientation was invisible due to chromatic fusion.

Procedures

Both experiments followed a standardized three-stage procedure: isoluminance adjustment, fear conditioning, and the main task.

First, subjective isoluminance of red and green was calibrated for each participant using a minimal flicker procedure [30], ensuring complete perceptual fusion of the chromatic gratings used in the main task.

Following isoluminance adjustment, a fear conditioning phase was conducted using the above-described CSs (grayscale gratings presented in the central visual field for Experiment 1, chromatic gratings presented in the symmetric peripheral visual field for Experiment 2), each presented for 500 ms with clear orientation visibility. Of these, 16 CSs were paired with the US (delivered during 410–500 ms after CS onset; CS+), while the other 16 CSs (orthogonal orientation) were presented without the US (CS-). Given that human participants can rapidly acquire fear conditioning even within a single trial [31], this trial number of CSs allowed for establishing the expected fear association. The orientation of the CS+ was counterbalanced across participants, and the presentation order of CS+ and CS- was randomized across trials. In contrast to the full fear conditioning phase, each top-up session followed the same protocol but with the number of trials reduced by half. The main task commenced immediately after fear conditioning.

Experiment 1 Main Task

Participants performed a 2-AFC orientation discrimination task, despite the flickering gratings fusing into a static yellow disk with no explicit orientation perception. Each trial began with a fixation point presented for 700–1300 ms. Subsequently, a CS+ flicker and a CS− flicker (each 2000 ms in duration) were presented sequentially, with their order and inter-stimulus interval (800–1200 ms) randomized. This design captured the contrast signal (i.e., unconscious fear) while minimizing trial-to-trial fluctuations in internal state. After the second flicker offset, participants were instructed to respond as accurately as possible to indicate which flicker was tilted clockwise or counterclockwise (no reaction time constraint). The next trial began 700–1300 ms after the response. A total of 80 trials were conducted (resulting in 80 epochs per condition [CS+, CS-] per participant), divided into two equivalent sessions. Before each session, a fear conditioning procedure was administered; a top-up procedure was conducted after half the trials in each session. Participants rested for at least 5 minutes between sessions.

Experiment 2 Main Task

Similar to Experiment 1, each trial presented one CS+ and one CS- in random order, with one key modification: both CS+ and CS- consisted of a pair of symmetric chromatic gratings with identical orientations (Fig. 2A). The inter-stimulus interval between CS+ and CS- was randomized between 1000 and 1200 ms.

The main experimental procedure comprised two blocks corresponding to attended and unattended attention conditions. While identical stimuli were presented across both conditions, participants were instructed to perform distinct tasks for each.

In the attended condition, participants completed a duration comparison task. CS+ grating pairs and CS- grating pairs were presented in random order, with each pair displayed for one of three possible durations: 800 ms, 1000 ms, or 1200 ms (Fig. 2B). The durations of the two grating pairs within each trial were always different, and participants were required to focus on identifying which pair had the longer presentation time. This condition included 3 blocks, with 60 trials per block.

In the unattended condition, participants performed a color detection task. They were instructed to ignore the CS+ and CS- pairs presented in the peripheral visual field, and to exclusively monitor the frequency of color changes in the central fixation point. The number of color changes per trial was randomized (0, 1, or 2 times; Fig. 2B), and participants were required to report the exact count of these changes. This condition also included 3 blocks of 60 trials each.

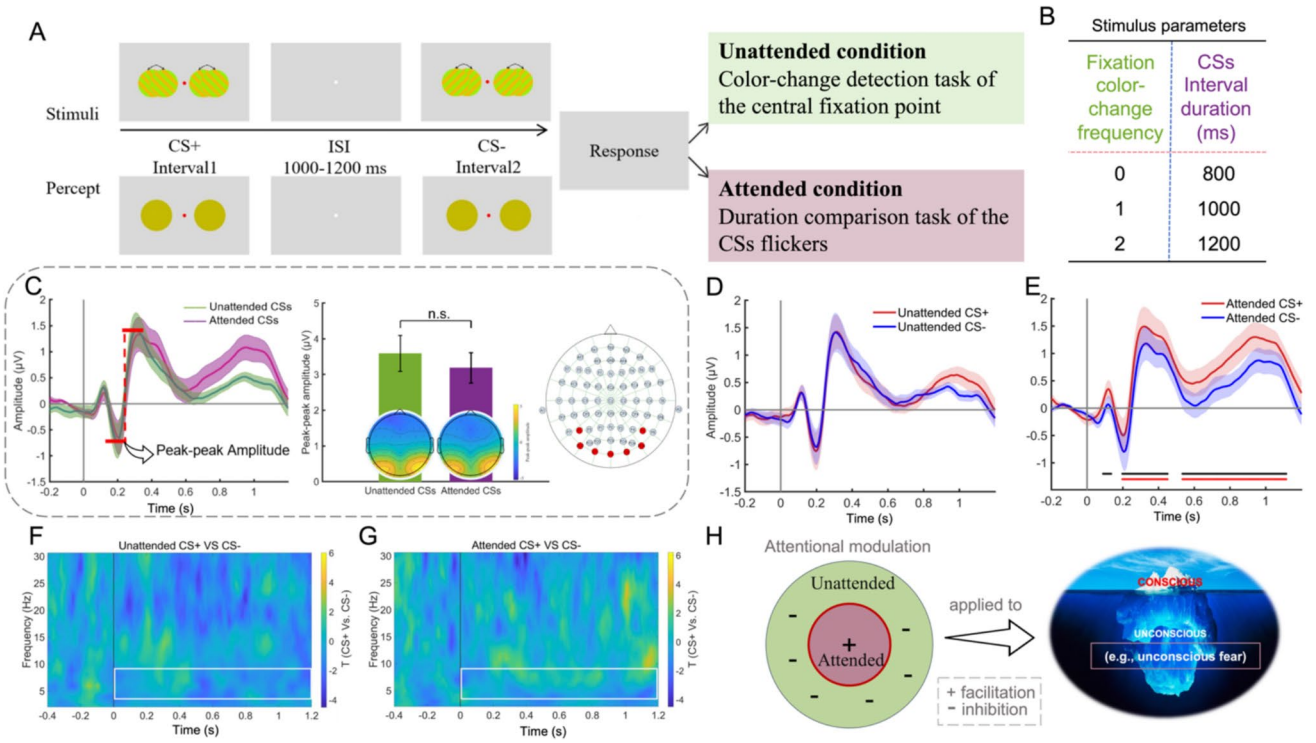


Fig. 2 Experimental design and electrophysiological results of Experiment 2, demonstrating attentional modulation of unconscious fear processing in safe contexts. **A, B** Schematic overview of the stimulus set and core task procedure for Experiment 2. Unlike Experiment 1, each conditioned stimulus (CS) comprised a pair of symmetrically presented flickers in the peripheral visual field, with both flickers matching in the same orientation. To manipulate top-down attention allocation, participants were assigned to one of two task conditions: in the Unattended condition, they counted the frequency of color changes in the central fixation point; in the Attended condition, they discriminated which of the two peripheral flickers had a longer presentation duration (targeting the temporal dimension of the CSs). **C** The peak-to-peak amplitude (spanning the N200–P300 components, averaged across CS+ and CS− trials) was computed to index the magnitude of stimulus-evoked visual cortical activity (left panel). This metric was statistically comparable between the Unattended and Attended conditions (middle panel), and—as expected—was most prominent in predefined peripheral regions of interest (ROIs; right panel). n.s., no significant difference, uncorrected. **D, E** Using the peripheral ROI for focused analysis, differential ERP responses (CS+ vs. CS−) were isolated for the (D) Unattended and (E) Attended conditions, respectively. Black dots denote uncorrected $P < 0.05$, whereas red dots indicate significance after cluster-based permutation testing ($P < 0.05$, corrected). Shaded regions surrounding each ERP waveform represent ±SEM. **F, G** Inter-trial coherence (ITC) analyses—including assessments of the theta frequency band (outlined by white squares, a signature oscillatory pattern identified in Experiment 1)—failed to detect significant CS+ versus CS− differences in either the (**F**) Unattended or (**G**) Attended condition. The color bar scale matches that of Fig. 1G for direct comparison. A cluster-based permutation test was used to correct for multiple comparisons. **H** Interim summary of the attentional modulation effect: unconscious fear responses are contingent on top-down attentional control, thereby extending attention-dependent modulatory effects (both facilitatory and inhibitory) from the domain of conscious processing to unconscious processing.

EEG Acquisition

EEG data were acquired using a Neuroscan SynAmps RT system with 64 Ag/AgCl electrodes embedded in elastic caps—Quik-Cap (Experiment 1) and Neoprene-Cap (Experiment 2)—following the international 10-10 system (Neuroscan Inc.). Continuous EEG signals were digitized at a sampling rate of 1000 Hz and online-referenced to a ground electrode (GND) positioned between CZ and CPZ. Electrode impedances were maintained below 5 kΩ for all channels.

Vertical and Horizontal Electrooculogram (VEOG/HEOG) Acquisition

Vertical electrooculogram (VEOG) and horizontal electrooculogram (HEOG) signals were recorded to monitor vertical and horizontal eye movements, respectively. HEOG was measured using two bipolar electrodes placed at the outer canthi of both eyes, while VEOG was recorded with two bipolar electrodes positioned above (VEOU) and below (VEOL) the left eye (Fig. 1E). VEOG signals were derived as the voltage difference between VEOU and VEOL, a

bipolar referencing approach that ensures accurate capture of vertical eye movement dynamics during experimental tasks.

EEG Preprocessing

Raw EEG data were analyzed using custom scripts adapted for the EEGLAB toolbox running on the MATLAB platform. Offline processing included down-sampling to 500 Hz and high-pass filtering at 0.5 Hz. Noisy channels were identified, rejected, and spherically interpolated (eeg_interp.m). Data were segmented around target onset (Experiment 1: −700 to 2700 ms; Experiment 2: −400 to 1600 ms), followed by artifact removal (eye blinks/movements) using independent component analysis (ICA; pop_runica.m). Epochs were then re-referenced to the average mastoid signal.

Fear-Related Signals in VEOG

It is important to note that previous studies have identified eye-related measures (e.g., increased pupil diameter, electromyography from electrodes above the left eyebrow) as indices of unconscious fear [21, 32]. Inspired by this work, we explored VEOG signals for correlates of unconscious fear. To control for volume conduction artifacts from adjacent frontal electrodes (proximal to VEOU recording sites), we re-referenced VEOG signals by subtracting the average activity of three adjacent frontal electrodes. For each participant, the fear-related VEOG signal was defined as the difference in mean activity between invisible CS+ and CS- epochs.

As illustrated in Fig. 1E, we identified such a physiological correlate of unconscious fear in Experiment 1; however, this signal was restricted to peri-ocular regions, with no fear-related activity observed in adjacent frontal electrodes. In Experiment 2, the VEOU electrode in the Neoprene-Cap was positioned farther from the eyelid and closer to the frontal cortex. To avoid overinterpretation, we refrained from using VEOG signals as a physiological marker of fear in Experiment 2.

Event-Related Potentials (ERP)

EEG data were further filtered with a 1–30 Hz bandpass filter. Epochs were extracted relative to stimulus onset and baseline-corrected using the mean voltage of the pre-stimulus interval (Experiment 1: −100 to 0 ms; Experiment 2: −400 to 0 ms). Trials with amplitudes exceeding ±100 μV were excluded, with a minimum of 80% of trials retained for each condition. ERPs were computed for each electrode, CS condition, and participant by averaging across processed epochs.

In Experiment 1, given our focus on visual processing and the central presentation of all chromatic flicker stimuli, six medial occipital electrodes (O1, Oz, O2, PO3, POz, PO4) were selected as the occipital region of interest (ROI). In Experiment 2, the occipital ROI (P5, P6, PO7, PO8, O1, Oz, O2) was determined based on the symmetric peripheral topography of early stimulus-evoked responses (see Fig. 2C for empirical validation). ERP signals from ROI channels were averaged for subsequent analyses.

We examined whether and when mean ERP responses to CS+ differed significantly from CS- using a nonparametric cluster-based permutation test to correct for family-wise error rates associated with multiple comparisons. The test proceeded as follows: (1) Paired-sample t-values were calculated at each time point for CS+ versus CS−; (2) Adjacent time points with significant t-values (uncorrected $P < 0.05$, two-tailed) were identified and grouped into clusters; (3) Cluster magnitude was quantified as the sum of absolute t-values across all time points within the cluster; (4) This procedure was repeated 1000 times with random permutation of CS+/- labels per participant, generating a permutation distribution of maximum cluster magnitudes; (5) Observed clusters were considered significant if their magnitude exceeded the 95th percentile of the permutation distribution (corrected cluster-level $P = 0.05$).

Time-Frequency Analysis

Time-frequency analysis was performed using Morlet wavelet transforms (newtimef.m function) in EEGLAB for MATLAB. In Experiment 1, epochs for decomposition were segmented from −700 to 2700 ms (extended to avoid edge artifacts), with wavelet cycle numbers increasing linearly from 2 cycles (3 Hz) to 13.33 cycles (100 Hz)—balancing temporal resolution at low frequencies and spectral stability at high frequencies. Decomposition yielded 200 time points spanning −328.8 to 2328.8 ms relative to stimulus onset. In Experiment 2, continuous EEG data were segmented from −2000 to 2500 ms relative to CS onset, with wavelet cycles ranging from 2 cycles (2 Hz) to 16 cycles (80 Hz), resulting in 1692 time points (−1441.9 to 1940.9 ms).

Two key indices were computed: (1) Inter-trial coherence (ITC; also referred to as phase-locking factor or phase-locking value), which quantifies the degree of phase synchronization across trials (range: 0 = no synchronization to 1 = perfect phase locking); (2) Event-related spectral perturbation (ERSP), which assesses relative changes in spectral power (i.e., increases or decreases) for invisible CS+ compared to invisible CS- at each time-frequency point.

Results

Previously Learned Unconscious Fear Distorts Visual Processing in a Safe Context

To test whether previously learned fear can still alter visual processing in a safe context, we first established a fear

conditioning task (Fig. 1A) in a threatening context in Experiment 1, then switched to a safe context (Fig. 1B)—rendering learned threat cues invisible and incorporating these subliminal cues into the main task (Fig. 1C).

In the fear conditioning task of Experiment 1 (threat context, Fig.1A), luminance gratings with either clockwise or counterclockwise orientations were used. For each participant, one orientation (CS+, 100% contingency) was repeatedly paired with electric aversive shocks (rated 7–8 on a scale of 0 to 10, where 0 indicated no pain at all and 10 indicated extreme pain). The other grating, with an orthogonal orientation, was never paired with shocks (CS−).

Subsequently, the main task switched to a safety context (Fig. 1B). To ensure a safe context, participants were explicitly informed that no further electric shocks would occur, and they practiced the main task beforehand to confirm this safety. Furthermore, we used a different stimulus set in the main task. That is, black-and-white luminance gratings were replaced with red-and-green chromatic gratings. These chromatic gratings were rapidly alternated with their anti-phase counterparts to achieve chromatic flicker fusion. Under these conditions, gratings of different orientations were consciously perceived as identical yellow disks (Fig. 1C)—a significant difference from the tilted black-and-white gratings perceived during fear conditioning.

To verify that orientation information was processed unconsciously during the main task and to direct attention to the CFF stimuli, we presented CFF stimuli in the central visual field (where attention is most concentrated). Participants were required to perform a 2-alternative forced choice (2-AFC) task (Fig.1C), indicating which flicker was in clockwise or anti-clockwise orientation. Task performance confirmed that participants could not discriminate grating orientation during the main task: after excluding one participant whose 2-AFC discrimination accuracy (ACC) reliably exceeded the 50% chance level (77.5% and 70% in Sessions 1 and 2, respectively), the remaining participants performed at chance (Session 1: $t(14) = -0.09$, $P = 0.930$, accuracy range: 0.375–0.650; Session 2: $t(14) = -0.95$, $P = 0.357$, accuracy range: 0.350–0.550; Fig. 1A). Only data from these remaining 15 participants were included in subsequent analyses of Experiment 1.

We hypothesized that previously established fear associations would generalize to the safe context and subsequently alter stimulus-evoked visual responses unconsciously. To better evaluate the temporal profile of such visually tagged unconscious fear responses in the safe context, CFF stimuli were presented for up to 2 seconds. This allowed continuous monitoring of responses at stimulus onset, offset, and during stimulus maintenance.

We first sought physiological evidence of unconscious fear in the safe context. Previous studies have shown that unconscious fear can be indexed by eye-related measures, such as increased pupil diameter and electromyography (EMG) signals recorded from electrodes above the left eyebrow [21, 32]. This inspired us to examine the EEG signals simultaneously recorded by bipolar electrodes for vertical electrooculography (VEOG), which were intentionally placed above (VEOU) and below (VEOL) the left eye (Fig. 1E left panel; see also Methods). We hypothesized that if unconscious fear occurred, fear-related information would induce a differential VEOG signal between unconscious CS+ and CS−. To control for volume conduction, we further subtracted the mean signal of three frontal electrodes surrounding the left eye (i.e., FPZ, FP1, F7, which showed distinct raw signal patterns) from the VEOG signal. As expected, we observed a significant difference between CS+ and CS− in the resulting signal (353–614 ms, summed $T = 69.57$, corrected $P = 0.01$; Fig. 1E right panel). Since all other aspects of the CSs were identical except for their threat-related associations, this unique electrooculogram response provides additional physiological evidence for the occurrence of unconscious fear.

Our primary interest was to determine whether unconscious fear alters visual processing in the safe context. We hypothesized that unconscious fear facilitates visual processing, potentially leading to differential event-related potentials (ERPs) between invisible CS+ and CS− flickers—particularly at occipital electrodes. To test this, we focused our analysis on an occipital region of interest (occipital ROI, Fig. 1F, middle upper panel) including six electrodes O1, Oz, O2, PO3, POz, and PO4. Using the mean ERP amplitude averaged across these six electrodes as the dependent variable and applying a cluster-based permutation test for multiple comparison correction, we identified three temporal clusters with significant differential ERPs (Fig. 1F left panel): 383–865 ms (summed $T = 159.4$, corrected $P = 0.002$), 1196–1547 ms (summed $T = 118.1$, corrected $P = 0.012$), and 1717–1888 ms (summed $T = 46.9$, corrected $P = 0.040$). To further characterize these findings, we assessed the spatial distribution of the mean differential ERP averaged across each cluster, confirming that the aforementioned unconscious fear responses were predominantly localized to occipitoparietal regions (Fig. 1F right panel). In contrast, the same analysis revealed no significant fear responses in frontal, central, or parietal ROIs (Fig. S1, note that the parietal ROI exhibited a similar response pattern to the occipital ROI, but failed to survive multiple comparison correction).

To investigate which neural oscillations mediate the communication of unconscious fear signals, we performed an inter-trial coherence (ITC) analysis—restricting it to slow neural oscillations (3–30 Hz), as these are better suited for inter-regional long-distance communication than fast oscillations [33–35]. Consistent with the ERP findings, we first conducted this analysis in the occipital ROI. Temporally,

three significant ITC clusters (Fig. 1G) were identified at 98–487 ms (cluster-based permutation test, summed T = 370.1, corrected P = 0.004), 1421–1621 ms (summed T = 248.7, corrected P = 0.030), and 1727–1982 ms (summed T = 192.4, marginally significant at corrected P = 0.058). In sharp contrast, no significant ITC effects were observed in frontal, central, or parietal ROIs (Fig. S2). To identify the frequency band most affected by unconscious fear, we conducted a paired-sample t-test comparing CS+ and CS− in the occipital ROI, using the mean ITC value averaged across 100–2000 ms post-stimulus onset as the dependent variable. Results showed significantly stronger ITC for CS+ than CS− in the high theta band (6–8 Hz), peaking at 7 Hz ($t_{(14)}$ = 4.62, uncorrected P < 0.001, FDR-corrected P < 0.05; Fig. 1H).

Although both ERP and ITC effects reflect unconscious fear processing, they exhibit distinct temporal and spatial patterns. Temporally, ITC effects are mainly confined to stimulus onset and offset, with only transient overlap with differential ERP responses (Fig. 1I). Spatially, ITC effects are concentrated at midline occipital electrodes (POz and Oz; Fig. 1G, three nested topographies), showing a more focused distribution than ERP effects. These temporal and spatial differences provide preliminary evidence that theta-band ITC effects and differential ERP effects represent two distinct neural processes underlying unconscious fear processing (see Discussion).

Collectively, the results of Experiment 1 demonstrate that previously learned associative fear can unconsciously enhance visual responses (i.e., distort vision) even in a safe context after the imminent threat has been removed. This distorted visual processing is represented by two distinct neural correlates in human occipital regions: visually evoked ERPs and theta coherence (ITC) peaking at 7 Hz.

Unconscious Fear Requires Attention to Distort Visual Processing

Following the findings of Experiment 1, we next asked: Is the visually-tagged unconscious fear response in the safe context purely stimulus-driven—distorting primary visual processing without requiring higher-order cognitive factors? Among such cognitive factors, top-down attention is characterized by its susceptibility to cognitive control and is a core target of current mainstream therapies for anxiety disorders [12–14]. Previous literature also identifies top-down attention as a fundamental factor modulating a wide range of unconscious processes related to language, vision, and emotion (for a review, see [36]). Clarifying whether attention is required for unconscious fear to distort vision in the safe context is critical for evaluating the efficacy of attention-based therapies in regulating such unconscious fear responses.

To address this question, Experiment 2 focused on top-down attention and explored its impact on the unconscious fear responses observed in Experiment 1. This research objective required unconscious fear cues to be displayed in an attended state and an unattended state, respectively, with comparisons between the two conditions to reveal the regulatory effect of attention.

To create these two attention conditions, we moved the subliminal fear cues originally presented in the central visual field to the peripheral visual field (Fig. 2A). Similar to Experiment 1, each trial still presented one CS+ and one CS- in random order, but with a key difference: both the CS+ and CS- were composed of a pair of two symmetric chromatic gratings of the same orientation (Fig. 2A). This symmetric presentation was used during both the fear conditioning task when grating orientations were explicitly visible (Fig. S3) and the main task when chromatic gratings were rendered invisible via CFF. This symmetrical design offers two critical advantages: first, compared to a single stimulus, symmetric presentation enhances visual input intensity, making participants' neural responses stronger and easier to detect attention-induced modulations; second, this symmetrical presentation balances visual salience on both sides, eliminating the bias toward one side that may occur with unilateral stimuli. This helped reduce visual distraction and related visual saccades, thus maintaining stable central fixation and ensuring chromatic flicker fusion.

The specific task under the attended condition was a duration comparison task: CS+ pairs and CS- pairs were presented in random order, with each grating pair having one of three possible durations (800, 1000 and 1200 ms, Fig. 2B). The durations of the two grating pairs in each trial were always different, and participants were required to focus on distinguishing which pair had a longer duration. The experimental results showed that participants' accuracy in this task was significantly higher than the chance level (accuracy: 0.73 ± 0.11, $t_{(22)}$ = 10.41, P < 0.01), demonstrating that they effectively engaged in the task and successfully focused their attention on the subliminal fear cues in the peripheral visual field.

Under the unattended condition, participants performed a color detection task: they were instructed to ignore the CS+ and CS- pairs in the peripheral visual field and solely monitor the frequency of color changes of the central fixation point. The frequency of color changes per trial was randomized (0, 1, or 2, Fig. 2B), and participants were required to provide accurate counts. High task accuracy (accuracy: 0.94 ± 0.06, $t_{(22)}$ = 52.26, P < 0.001) confirmed that participants maintained robust central attention, effectively leaving peripheral CFF stimuli in an unattended state.

Prior studies [37–39] have demonstrated that the human brain is capable of unconsciously processing orientation information and inducing the orientation adaptation

aftereffect—namely, the tilt-after effect (TAE). Critically, the TAE elicited by unconscious orientation information could be impervious to attentional modulation [37]: it occurs consistently under both attended and unattended conditions, with no significant difference in effect magnitude observed between the two attentional states (but also note that such TAE effect induced by invisible orientation processing could increase with attention under certain carefully designed conditions [38]). From this perspective, our study adopted an experimental design in which orientation information was fused to invisible stimuli and tested under both attended and unattended conditions. Therefore, any observed differences between these two attentional states can only reflect the processing of fear associated with invisible orientation cues, rather than loss of the brain's inherent capacity to decode orientation information itself under unattended conditions.

Based on the two tasks described above, another key methodological advancement of Experiment 2 over Experiment 1 lies in the elimination of task-relevance confounds (also see Discussion). In Experiment 1, participants completed an orientation discrimination task, which was inherently task-relevant to the core associative feature (orientation) of fear conditioning—introducing potential interference despite the subliminal nature of the orientation cues. In contrast, both the duration discrimination task (attended condition) and central fixation color change detection task (unattended condition) in Experiment 2 were orthogonal to the orientation of the CS+ and CS- pairs. This design ensures that observed differences between the two attention conditions cannot be attributed to task-relevance effects, but rather reflect the intrinsic link between top-down attention and unconscious fear responses in safe contexts.

We first compared the intensity of stimulus-evoked visual responses under attended and unattended conditions. To quantify this intensity, we calculated the mean peak-to-peak amplitude of the N2 and P3 components of stimulus-evoked vERPs (average of CS+ and CS−, Fig. 2C left panel) calculated using bilateral electrodes in lateral occipitoparietal regions (Fig. 2C right panel). For early vERPs (~400ms post-stimulus onset), the unattended condition and the attended condition shared comparable peak-to-peak amplitude ($t_{(22)}$= 1.21, P =0.240, Fig. 2C middle panel)—ruling out the possibility of significant suppression of early visual activity due to lack of attention in the unattended condition. As shown, the distribution of peak-to-peak amplitude across all scalp electrodes is consistent with the retinotopic activation pattern, wherein bilateral peripheral stimuli elicit activation in the lateral occipital electrodes. Accordingly, this symmetric peripheral ROI (Fig. 2C right panel) was adopted for all subsequent analyses in Experiment 2.

ERP analysis in the attended condition (Fig. 2E) revealed significant differential vERPs (CS+ vs. CS−) in two clusters: 196–452 ms (summed T = 159.5, corrected P = 0.042) and 532–1116 ms (summed T = 122.2, corrected P = 0.002) post-stimulus onset. At a cluster threshold of $P < 0.05$, CS+ induced significantly greater ERP responses than CS−. Additionally, 88–136 ms post-CS onset, CS+ induced significantly higher average ERP amplitude than CS−, though this effect did not survive multiple comparison correction (summed T = 31.0, uncorrected $P < 0.05$, corrected P = 0.392). These results demonstrate prolonged differential ERP representation during stimulus presentation, replicating unconscious fear effects under attended conditions.

ERP analysis in the unattended condition (Fig. 2D), however, revealed no significant vERP-based unconscious fear response between unconscious CS+ and CS- in each of the three clusters previously identified in the attended condition. Furthermore, the contrast between attended vs. unattended conditions using one-tailed paired t-test revealed the amplitude of this unconscious fear response decreased if attention was directed away (88–136 ms: $t_{(22)}$=-1.54, P =0.068; 196–452 ms: $t_{(22)}$=−1.81, P =0.042; 532–1116 ms: $t_{(22)}$=-1.53, P =0.070). Results above thus provide compelling evidence showing that unconscious fear responses in safe contexts are present in the attended condition only but completely absent in the unattended condition.

In sharp contrast, ITC analysis revealed no significant ITC differences between unconscious CS+ vs. CS− under both unattended (Fig. 2F) and attended (Fig.2G) conditions in Experiment 2 (cluster-based permutation test, all corrected $P > 0.05$)—a notable departure from Experiment 1.

Collectively, the above findings provide compelling evidence that top-down attention can modulate unconscious fear responses in a safe context, thus extending attention's regulatory effects on conscious stimulus processing (i.e., facilitating the processing of some stimuli while inhibiting that of others) to a broader spectrum of unconscious processes represented by unconscious fear (Fig. 2H).

Attention-Dependent Broad-Alpha Activity Bidirectionally Regulates Unconscious Fear

Why was the vERP-based unconscious fear response present in the attended condition but completely absent in the unattended condition According to theoretical accounts [26], alpha oscillations can bidirectionally modulate unconscious processes prior to the emergence of perceptual awareness, serving two opposing functions to enhance signal-to-noise ratio (SNR). On one hand, alpha oscillations can suppress certain unconscious processes by eliminating them as noise, with higher alpha power enabling more effective noise reduction. On the other hand, they can facilitate specific unconscious processes by amplifying the signal information that is poised for expression, such that greater alpha power correlates with enhanced signal strength. It is proposed that the brain employs this

alpha-band bidirectional modulation to amplify target signals and suppress irrelevant noise, thereby selecting emerging signals that ultimately gain access to conscious experience. However, empirical evidence supporting this bidirectional regulatory role of alpha oscillations in unconscious processes remains scarce.

In the present study, the pattern of unconscious fear effects across the two attentional conditions aligns precisely with the framework of signal enhancement under attention and noise suppression in the absence of attention. Guided by this insight, we further investigated the relationship between alpha oscillations and unconscious fear responses in each attentional condition.

We first tested the possibility that top-down attention suppresses unconscious fear via alpha oscillations under the unattended condition (Fig. 3A, Hypothesis 1). As alpha oscillations are thought to mediate suppression of the peripheral visual field [40–42], we hypothesized that post-stimulus alpha power within the lateral visual ROI might be elevated in the unattended condition relative to the attended condition. To address this hypothesis, we computed neural oscillation power across a broad frequency range and compared the unattended and attended conditions.

Consistent with this prediction, we observed stronger broad-alpha activity (4–20 Hz, Fig. 3B, red square) following CS onset in the unattended condition. This increase in alpha power emerged at around 200 ms post-stimulus and persisted until stimulus offset—a time window that overlaps with the period of significant unconscious fear responses in the attended condition (Fig. 2E). This temporal correspondence suggests that the heightened and sustained alpha activity suppressed unconscious fear responses. Framed within the signal-noise framework, the unconscious fear response in the attended condition (construed as a signal) was eliminated as noise by alpha oscillations in the unattended condition (i.e., a noise reduction process), thereby preventing the manifestation of differential vERP responses. Importantly, paired t-tests revealed no significant difference in broad-alpha oscillation power between CS+ and CS− stimuli (paired *t*-test,

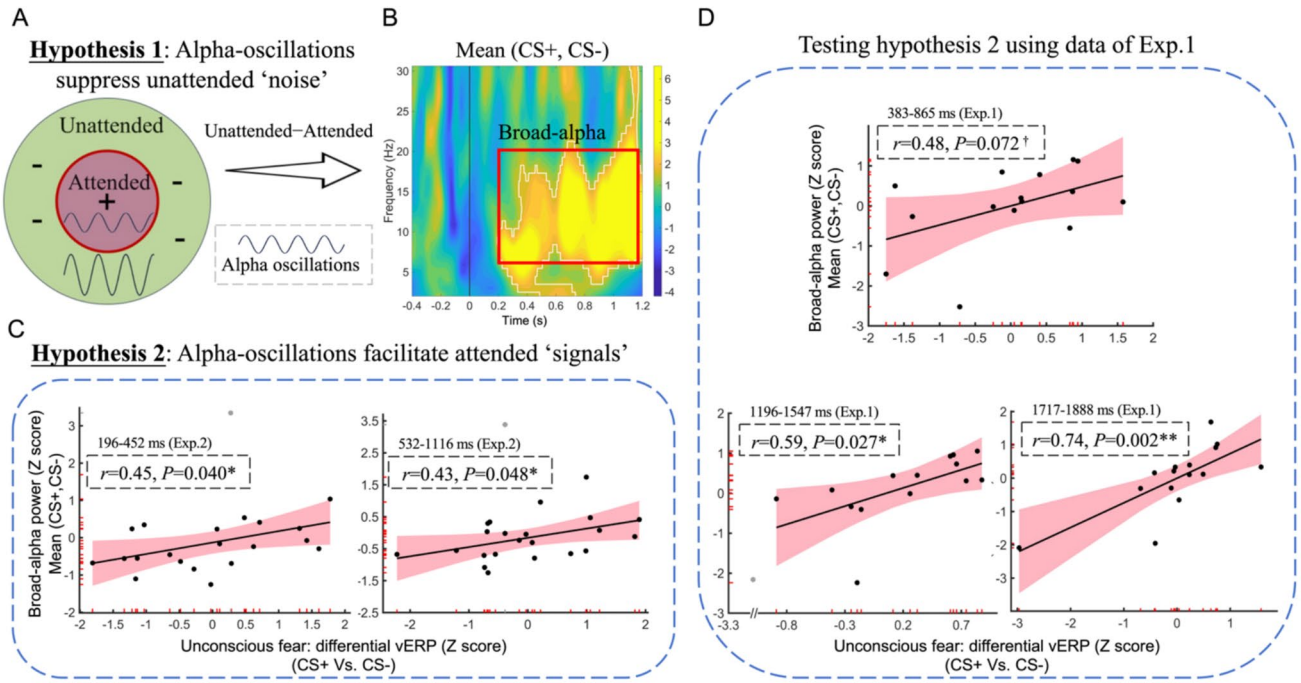


Fig. 3 Hypotheses and supporting evidence illustrating how top-down attention recruits alpha oscillations to bidirectionally modulate unconscious fear processing. A Hypothesis 1 posits that robust post-stimulus alpha-band oscillations are induced under the unattended condition, which suppresses unconscious fear processing by treating it as neural "noise". **B** Empirical evidence for Hypothesis 1. White-outlined regions indicate statistically significant increases in broad-alpha power under the unattended versus attended condition. The red square marks the resulting region of interest (ROI) in the broad alpha band, which covers the classical alpha band (6–13 HZ) with broader band width, and was subsequently extracted and used for downstream statistical analyses. **C** Hypothesis 2 proposes that broad alpha oscillations facilitate the encoding and propagation of survived 'signals' under the attended condition, thereby correspondingly amplifying unconscious fear responses in this context. Pearson correlation analyses of data from Experiment 2 corroborated this hypothesis, revealing a significant positive correlation between post-stimulus broad alpha power and the amplitude of unconscious fear responses across all included participants. **D** Hypothesis 2 received additional empirical support from the data of Experiment 1. For Panels **C** and **D**, black dots denote individual participant data included in the correlation analyses, while gray dots represent outliers (normalized Z > 3 or < −3) that were excluded from the correlation analyses to ensure statistical validity. † $P < 0.1$; * $P < 0.05$; ** $P < 0.01$.

196-452ms: $t_{(22)}$=0.72, P =0.480; 532-1116ms: $t_{(22)}$=1.28, P =0.214). Collectively, these findings demonstrate that broad-alpha oscillations do not directly encode unconscious fear (i.e., they do not differentiate between CS+ and CS−) but instead abolish unconscious fear responses in the unattended condition.

We next examined whether top-down attention facilitates signal expression via alpha oscillations in the attended condition (Fig. 3C, Hypothesis 2). The robust unconscious fear response observed in the attended condition indicates that this process was prioritized as a signal rather than suppressed as noise. Here, we specifically tested whether the strength of this signal would correlate positively with broad-alpha power. We predicted that if unconscious fear were treated as a prioritized signal and amplified by alpha-band activity, a positive correlation between these two measures would be observed.

To evaluate this prediction, we computed differential ERP amplitudes (CS+ minus CS−) to index unconscious fear and averaged post-stimulus alpha-band power (across CS+ and CS−) to quantify alpha activity for each participant. A Pearson correlation analysis was then conducted to assess the relationship between these two metrics. As shown in Fig. 3C, results revealed a significant positive correlation between differential ERP amplitudes and mean broad-alpha power during the two temporal clusters where unconscious fear responses were most prominent (Cluster 1: 196–452 ms, r = 0.45, P = 0.040; Cluster 2: 532–1116 ms, r = 0.43, P = 0.048). It is critical to note, however, that this positive correlation could potentially be confounded by a scaling effect—a phenomenon in which the magnitude of a condition-dependent effect varies with the baseline activity level. To rule out this confounding factor, we adopted the mean peak-to-peak amplitude of the N2 and P3 components of stimulus-evoked vERPs (Fig. 2C left panel) as a baseline index to quantify baseline activity; notably, no significant correlation (Fig. S4) was detected between this alternative baseline index and the unconscious fear effect of interest. This result confirms that the observed positive correlation between the unconscious fear and mean alpha oscillatory power is not attributable to a scaling effect, but rather represents a genuine association between the two variables.

Collectively, above results support the hypothesis that unconscious fear is prioritized as a signal and is thus protected or facilitated by alpha-band activity in the attended condition, providing direct empirical evidence that attention can recruit alpha oscillations to enhance unconscious processes such as unconscious fear.

To validate the reliability of this novel finding, we cross-validated the results across Experiment 1 and Experiment 2, testing whether the alpha-mediated facilitation of unconscious fear responses could generalize to the experimental paradigm of Experiment 1. Unlike Experiment 2 (which used bilateral peripheral CFF flickers and covert attention with a peripheral discrimination task), Experiment 1 presented CFF flickers in the central visual field, required overt attention to the flickers, and employed an orientation discrimination task (with orientation stimuli rendered invisible via perfect fusion). We replicated the same analytical pipeline to quantify unconscious fear responses and post-stimulus alpha-band activity, and observed a consistent positive correlation (Fig. 3D) between these two measures across all three temporal clusters previously reported in Fig. 1F (Cluster 1: 383–865 ms, r = 0.48, P = 0.072, marginally significant; Cluster 2: 1196–1547 ms, r = 0.59, P = 0.027; Cluster 3: 1717–1888 ms, r = 0.74, P = 0.002). Despite differences in stimulus presentation, attentional demands, and task design across the two experiments, this cross-experimental replication provides compelling evidence that attention reliably recruits broad-alpha oscillations to facilitate unconscious fear processing if these subliminal cues were in attended state.

Discussion

The current study demonstrates that previously learned fear does not subside after transferring from an old threatening context to a new safe context; instead, when attended, it continuously and unconsciously alters visual sensory processing during the subliminal presentation of fear-associated cues. The differential visual ERP between unconscious CS+ and CS- serves as a reliable neural marker for unconscious fear. More importantly, this unconscious fear response requires top-down attention as a prerequisite: in the attended condition, broad alpha activity is engaged to proportionally facilitate the unconscious fear response. In contrast, in the unattended condition, a further increase in broad alpha activity is accompanied by a complete absence of the visually tagged unconscious fear response. Collectively, findings here indicate top-down attention may gate unconscious fear via broad alpha oscillations, flexibly prioritizing it as a signal or suppressing it as noise.

Across two experiments, we replicated the finding that previously learned fear cues can alter visual processing in safe contexts. Prior studies have found that unconscious fear sensitizes visual processing in threatening contexts. A growing perspective in recent years [6] suggests that associative learning of fear-related information may bypass the amygdala and directly initiate rapid, precise threat evaluation in the primary sensory cortex. For example, a monkey study [5] reported a transient increase in the firing rates of V1 neurons induced by unconscious fear stimuli as early as 40 ms, but this effect was extremely short-lived and faded rapidly. In contrast, fear-related differential ERPs originating from the amygdala emerge later—at approximately 76 ms

for supraliminal fearful faces [20] and 88 ms for subliminal ones [43]—and persist longer over time. In the current study, we also observed early fear responses in scalp EEG signals (uncorrected $P < 0.05$, 80–140ms shown in Fig. 2E). However, likely due to the extremely small amplitude of early visual ERP responses (e.g., the C1 component, [44]) measurable via EEG technology, these early effects did not survive multiple comparisons correction. Practically, these findings suggest that early visual responses may not be sufficient as robust markers for monitoring unconscious fear signals.

Instead, our results indicate that relatively late (≥200ms) visual ERP responses may serve as more reliable markers for unconscious fear. Specifically, sustained ERP-based unconscious fear responses (FDR-corrected) were observed in both EEG experiments. These fear-related visual responses emerged relatively late but consistently exhibited neural differences between unconscious CS+ and CS-. This suggests that under attended conditions, unconscious threat cues can persistently alter visual processing in a stimulus-driven manner. These findings demonstrate that even when real threats are absent and the contexts become safe, subliminal threat cues (previously learned) can still unconsciously modulate visual processing when they fall within the attentional focus.

Beyond ERP effects, Experiment 1 revealed that theta-band intertrial coherence (ITC)—peaking at 7 Hz and restricted to midline occipital electrodes—also characterizes unconscious fear responses, with CS+ enhancing ITC. However, the temporal overlap between ITC and ERP effects was limited, with most time windows showing dissociation. More importantly, we failed to replicate the ITC effect in Experiment 2. Previous studies have shown that theta ITC not only encodes fear signals [35] but is also sensitive to changes in the stream of consciousness, such as sensory change detection [45], episodic memory encoding [46], fluctuation in time perception [47], and dynamic video watching [48]. Compared to Experiment 1—where conscious experience during the two CS flickers was uniformly stable (yellow discs and a fixed fixation point for 2 s)—Experiment 2 involved more temporal variations in conscious experience, including changes in fixation point color and greater variance in the duration of the two flickers. From this perspective, the dynamic stream of consciousness in Experiment 2 might have induced large variations in ITC measures, making it harder to detect another subtle independent effect induced by unconscious fear. Collectively, this again indicates that late vERP responses, relative to the other two indices (early vERP and ITC), may serve as a more reliable and sensitive EEG index to quantify unconscious fear responses in safe contexts.

By employing this index to quantify unconscious fear, our findings regarding its attentional dependence provide a critical extension to the longstanding debate surrounding the interplay between emotion and attention (for review, see [49, 50]). Historically, the vast majority of investigations in this domain have relied on supraliminal emotional stimuli. Early behavioral studies demonstrated that task-irrelevant supraliminal emotional cues disrupt task performance[51], which was taken as evidence for automatic, attention-independent emotional processing—a claim corroborated by neuroimaging studies [52, 53] documenting subcortical amygdala and scalp EEG responses to such stimuli. However, subsequent neuroimaging studies [50, 54] with more rigorous attention-control protocols challenged this framework, showing that emotional processing is impaired or even completely abolished when stimuli are rendered unattended (e.g., [23, 55]). The attentional load theory [56] later reconciled this discrepancy: under conditions of low attentional load, residual cognitive resources permit automatic emotional processing, whereas high load eliminates this capacity due to the exhaustion of available resources [57].

In sharp contrast, only a small subset of studies have used subliminal fear stimuli [5, 24, 25] and explored the relationship between attention and unconscious fear, although these works suffer from key limitations. For instance, Li *et al.* restricted their inquiry to fear-inducing contexts[5], while Wang *et al.* and Doradzińska *et al.* failed to effectively capture the impact of unconscious fear on sensory processing[24, 25]. After systematically addressing these aforementioned limitations, the present study nonetheless detected the unconscious fear effect only under attended conditions. This result thus more rigorously confirms the attentional dependence of unconscious fear responses, delivering a robust supplement to the existing literature.

What is the specific rule for top-down attention to regulate unconscious fear? A core theory posits that task relevance is the key regulatory factor [58]: top-down attention can not only enhance task-relevant unconscious processes but also weaken those task-irrelevant. While this theory can explain the unconscious fear response in Experiment 1, it cannot account for the results of Experiment 2. Orientation-associated fear was relevant to the orientation discrimination task in Experiment 1 but irrelevant to both the duration discrimination task and the fixation color monitoring task in Experiment 2. If task relevance were the sole factor, no unconscious fear responses should have been observed in either condition. After controlling for task-relevance, findings of Experiment 2 thus may reflect an intrinsic link between top-down attention and unconscious fear responses. This insight extends our prior knowledge on how top-down attention modulates unconscious processes (for prior review, see [36]), suggesting attentional state is a more critical factor than goal-relevance, with the latter potentially modulating unconscious process by altering whether the target unconscious processes is being 'attended' or not.

Another critical finding of the current study is that alpha-band oscillations may serve as an important medium for top-down attention to regulate unconscious fear processing. It is well established that alpha activity plays an "inhibitory" role in suppressing distractors [40, 41]. For instance, when stabilizing attentional focus on one hemifield, alpha activity decreases in the hemisphere receiving target stimulus input and increases in the contralateral hemisphere to suppress irrelevant distractors [42]. While the inhibitory role of pre-stimulus alpha activity has been well-documented, the function of post-stimulus alpha activity remains insufficiently understood [59]—particularly regarding its roles in regulating unconscious processes. In the present study, we found that post-stimulus alpha exerts a bidirectional regulatory effect: if unconscious fear is in an unattended state, enhanced alpha effectively suppresses it. Conversely, if unconscious fear is in an attended state, enhanced alpha is associated with more pronounced unconscious fear responses—a novel finding replicated across two experiments. These results thus represent significant progress in this research direction.

Such a bidirectional regulatory effect of alpha-band oscillations on unconscious fear offers new insights into the emergence of consciousness. To elaborate, previous research [26] has hypothesized a specific neural dynamic preceding conscious awareness: when a salient stimulus suddenly enters the attentional focus, it first triggers increased alpha activity (event-related synchronization, ERS) prior to the emergence of conscious awareness of the stimulus. This alpha ERS is proposed to suppress background noise and enhance target signals—elevating the signal-to-noise ratio (SNR)—before conscious perception of the target is formed [26]. While the current study does not directly investigate dynamic changes before and after the emergence of consciousness, it uses unconscious fear as a model to test this hypothesis, providing clear empirical evidence that alpha activity can indeed exert bidirectional inhibitory-excitatory regulation on unconscious processes.

To synthesize the alpha-related findings across both attended and unattended conditions, we propose an Alpha Denoising Model (ADM, Fig. 4A) to delineate how top-down attention recruits broad-alpha oscillations to concurrently facilitate certain unconscious processes (treated as signals, e.g., unconscious fear in the attended state, Fig. 4B) while suppressing others (treated as noise, e.g., unconscious fear in the unattended state, Fig. 4B) in the brain. This mechanism generates emerging signals with an elevated SNR prior to their access to conscious awareness, thereby shaping the selection of unconscious processes that ultimately transition into conscious experience.

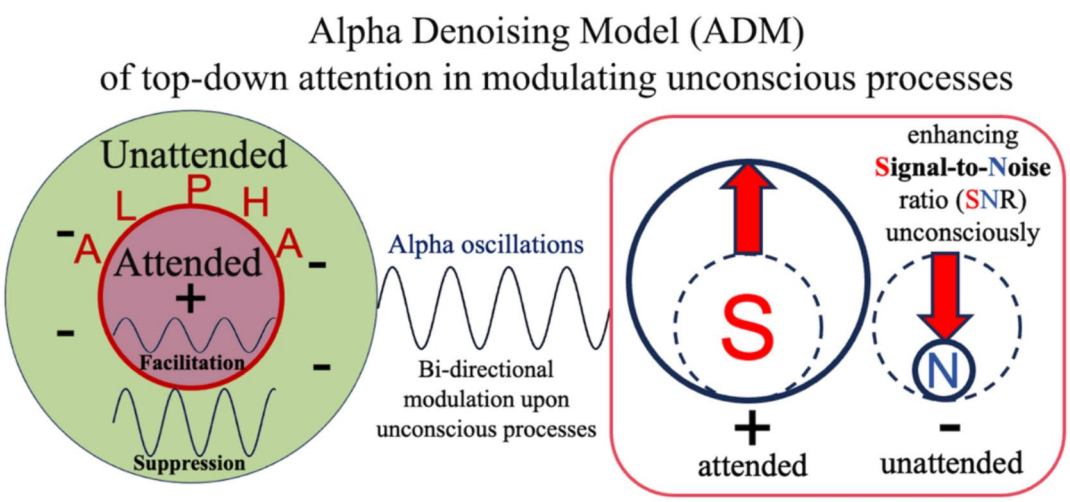
Our findings may also hold clinical significance. Individuals with anxiety disorders are known to be more prone to focusing on or ruminating about threat cues and stressful contexts in daily life [60, 61]. This undoubtedly increases and prolongs subjective fear experiences. However, a long-overlooked possibility is that such top-down attention may also foster the persistent representation of fear signals at the unconscious level. Our findings demonstrate that fear signals can still be unconsciously represented and exert effects (i.e., distorting visual processing) in safe contexts, resulting in a conflict between conscious safety and unconscious fear.

Unconscious fear representations engage the amygdala-centered subcortical fast-response pathway [21] (or rapid plastic reorganization of sensory cortices [6]), while conscious safety representations are mediated by the frontal lobe-centered cortical slow-response system [22, 62]. Some perspectives suggest that the conflict between these two systems may constitute one of the pathogenic mechanisms of phobias and anxiety disorders [11, 63–65], but the consequences and regulatory mechanisms of this conflict remain poorly understood (also see new advances [66, 67]). Addressing this gap, the present study provides a feasible paradigm for inducing such a conflict (i.e., evoking unconscious fear in the attended condition) and mitigating it (i.e., suppressing unconscious fear in the unattended condition) under well-controlled experimental settings, thereby enabling further investigation of the mechanisms underlying the regulation of unconscious fear. However, it should be noted that the present study is limited by its correlational nature of findings. Future studies using neural intervention methods such as EEG-compatible transcranial magnetic stimulation (TMS) and temporal interference (TI) are awaited to causally test whether this bidirectional alpha modulation could be replicated and how these broad-alpha oscillations causally modulate unconscious fear responses across different attentional states.

In terms of psychological interventions, this study inspires a novel approach based on attentional state switching. Previous research has demonstrated that both directing attention toward a subliminal fear cue [16, 19, 68] and diverting attention away from it [69] can reduce certain aspects of fear (reviewed in [17]). These two approaches correspond exactly to the attended and unattended conditions in Experiment 2 of the present study, indicating that both may offer a window for the re-editing of fear memories. Building on this, it becomes critical to test whether alternating between these two conditions can serve as a new method for unconsciously re-editing fear-related memories.

A major limitation of the present study is that it only recruited healthy college student participants and has not been validated in clinical patient populations. Future research should systematically examine whether clinical patients—who have been shown to be more responsive to subliminal threatening stimuli [70]—might exhibit (1) stronger alpha facilitation of unconscious fear

A



B

How ADM works: Taking unconscious fear as an example

Exemplar process	Attentional state	Treated as	Effect of alpha oscillations	Observed outcome
Unconscious fear	Attended (+)	Signal	facilitation	Unconscious fear distorts visual processing
	Unattended (-)	Noise	suppression	No visual distortion

Fig. 4 Alpha Denoising Model (ADM), a newly proposed framework that elucidates how top-down attentional control recruits broad-alpha oscillations to bidirectionally modulate unconscious information processing. **A** At a given neural region (e.g., the visual cortex), the amplitude of alpha-band oscillations is modulated by top-down attention, exhibiting amplified alpha power when the region lies outside the attentional focus and attenuated alpha power when it falls within the attentional focus. Critically, these two distinct patterns of alpha oscillatory activity reflect opposing regulatory effects on unconscious processes: amplified alpha oscillations in non-prioritized regions likely reflect the suppression of extraneous unconscious processing, whereas the alpha oscillatory activity in attentionally prioritized regions likely reflects the facilitation of unconscious computations, with more robust alpha oscillatory activity corresponding to stronger facilitation of the targeted unconscious processes. This mechanism generates unconscious neural signals with a markedly elevated signal-to-noise ratio (SNR), enabling their propagation to downstream neural circuits for further processing and analysis—even though certain subsets of these signals (e.g., the unconscious fear signals investigated in the present study) never gain access to conscious awareness. **B** Taking unconscious fear processing as a paradigmatic experimental model, this panel delineates the mechanistic implementation of the ADM in bidirectionally regulating whether and how previously learned fear unconsciously distorts primary visual processing in the safe context.

in attended conditions, or (2) reduced alpha suppression of unconscious fear in unattended conditions relative to healthy individuals. Additionally, future work should carefully assess whether the aforementioned intervention methods can effectively reduce clinical anxiety symptoms in patient samples or delay the progression of anxiety symptoms in the general population.

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Conflict of interest The authors declare that there are no conflicts of interest.

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