Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Attention Renders Sensory Contents into Conscious State via Content-invariant Frontal-Posterior Coupling in Humans

Liang Wang

lwang@psych.ac.cn

Institute of Psychology, Chinese Academy of Sciences https://orcid.org/0000-0001-9434-7571

Xilei Zhang

Institute of Psychology, Chinese Academy of Sciences

Yiru Lin

Institute of Psychology, Chinese Academy of Sciences

Zhuoren Jin

Institute of Psychology, Chinese Academy of Sciences

Kai Zhang

Department of Neurosurgery, Beijing Tiantan Hospital, Capital Medical University

Wenjing Zhou

Tsinghua University

Sheng He

Institute of Biophysics, Chinese Academy of Sciences

Yi Jiang

Institute of Psychology, Chinese Academy of Sciences https://orcid.org/0000-0002-5746-7301

Chao Zhang

Department of Neurosurgery, Beijing Tiantan Hospital

Article

Keywords:

Posted Date: November 3rd, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10945410/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: There is **NO** Competing Interest.

Attention Renders Sensory Contents into Conscious State via Content-invariant Frontal-Posterior Coupling in Humans

Xilei Zhang[1,2], Yiru Lin[1,2], Zhuoren Jin[1,2], Kai Zhang[3], Wenjing Zhou[4], Sheng He[5], Yi Jiang[1,2], Chao Zhang[3]*, Liang Wang[1,2]*

[1]State Key Laboratory of Cognitive Science and Mental Health, Institute of Psychology, Chinese Academy of Sciences, Beijing, China.
[2]Department of Psychology, University of Chinese Academy of Sciences, Beijing, China.
[3]Department of Neurosurgery, Beijing Tiantan Hospital, Capital Medical University, Beijing, China.
[4]Epilepsy Center, Tsinghua University Yuquan Hospital, Beijing, China.
[5]State Key Laboratory of Cognitive Science and Mental Health, Institute of Biophysics, Chinese Academy of Sciences, Beijing, China.

*Liang Wang. Email: lwang@psych.ac.cn

*Chao Zhang. Email: zhangchao94306@163.com

Abstract:

Although attention promotes conscious perception, how it does so remains unclear. Human neuroimaging research has richly characterized attentional modulation upon visual processing, yet it remains unclear which of its components act as precursors of consciousness, which constitute consciousness itself, and which merely reflect post-perceptual, response-related operations. Combining a newly developed psychophysical paradigm with intracranial electroencephalography (iEEG), we addressed this issue in the human brain. Behavioral results from the psychophysical experiment and its replication showed that top-down attention plays a preparatory role: it promotes visual consciousness not directly, but by enabling attentional capture specific to salient stimuli. iEEG then revealed that early attentional preparation unfolds in a module-dependent manner, differing between the posterior brain (sensory module) and the frontal brain (attention module). We further dissociated two neural signals—one tracking the rapid rise and decay of visual consciousness, the other supporting post-perceptual responses through global late (>600 ms) content retrieval—thereby isolating a conscious window (~250–550 ms) from its preconscious and post-perceptual confounds. Finally, coherence analyses revealed the predicted frontal–posterior coupling (~4 Hz) restricted to this window. Critically, this coupling encoded only the binary on/off state of conscious awareness, whereas fine-grained contents were persistently encoded in the posterior brain. Together, these findings provide pioneering evidence that attention does not promote consciousness directly by itself; rather, it engages a content-invariant frontal–posterior coupling mechanism—not an earlier sensory enhancement mechanism or a later global content broadcast mechanism—to render sensory contents into an explicit conscious state.

Keywords: Consciousness; Attention; Frontal-posterior coupling; intracranial EEG; Attentional coupling model

Main text

The emergence of subjective consciousness in the brain presents a multifaceted puzzle, with attention occupying a central position. Despite the everyday experience that what we consciously perceive is usually what we are attending to, ongoing debate (*1-7*) revolves around whether—and which—interactions between attention and sensory processing are necessary for conscious perception. In particular, it remains poorly understood which attentional processes act as precursors of consciousness, which constitute the conscious process itself, and which merely reflect post-perceptual, response-related operations.

One possibility is that conscious signals already arise during the early attentional modulation of visual activity. Previous transcranial magnetic stimulation studies (*8, 9*) implicate early visual activity in gating visual awareness (but see also (*10*)), and attention readily amplifies early visual activity (*11, 12*) beginning as early as within 100 ms after stimulus onset. Consistently, the visual awareness negativity (VAN)—a candidate early event-related electrophysiological (ERP) marker of awareness peaking at around 200 ms (*13-18*)—is also markedly enhanced by attention (*19-21*) (i.e., larger amplitude when attended). These findings accord with the localist perspective (*22, 23*), which proposes that posterior brain activity alone is sufficient to support conscious experience. However, a critical question remains unresolved: whether these early attentional modulations of posterior brain activity constitute a precursor of consciousness or consciousness itself.

Conversely, the globalist perspective (*24-27*) predicts that early sensory processing alone cannot generate consciousness. Rather, such processing must interact with the frontal brain—a multifunctional hub supporting the control of attention (*28-31*), working memory (*32, 33*), and action-related operations (*34-36*) (e.g., reasoning, planning, decision-making, and reporting)—to achieve conscious access. In line with this view, previous studies (*37, 38*) have demonstrated distinct long-range functional coupling patterns corresponding to different perceptual categories (e.g., discriminating houses from faces).

However, it is critical to note that consciousness-related activity in the frontal brain, if present at all, may be readily confounded with post-perceptual processing (*39*). For example, the late frontal P3b component (>300 ms), previously considered a neural correlate of consciousness (NCC) (*40*), has been shown to diminish or disappear entirely in no-report paradigms (*41*), suggesting that it may not be a reliable NCC biomarker (for review, see (*14*)). Therefore, disentangling which posterior–frontal interactions support consciousness per se and which support post-perceptual responses is essential for understanding the mechanisms of consciousness, yet this remains a significant methodological challenge.

Combining a newly developed psychophysical paradigm with intracranial EEG (iEEG), the present study aims to dissociate the distinct stages at which attention modulates visual saliency processing, and to evaluate which form of neural modulation is the most plausible candidate substrate of consciousness. Using this paradigm, we quantitatively separated two attentional

processes (**Experiment 1** and its replication): attention allocated top-down to the location of the target stimulus, and attention captured bottom-up by a subsequently presented visible target (but not by an invisible image). In addition, we isolated an independent index of consciousness to test which attentional component is related to conscious perception. If early attentional modulation in posterior brain regions directly gives rise to consciousness, then top-down attention is expected to show a linear relationship with the measure of consciousness; conversely, if posterior brain regions must be coupled with the frontal brain to generate consciousness, then this correlational relationship might be alternatively tied to attentional capture. Leveraging the high spatiotemporal resolution of iEEG (21 patients with epilepsy; **Experiment 2**), we further characterized how attention differently modulates frontal and posterior brain activity at an early stage, induces frontal-posterior coupling at an intermediate stage, and interfaces with behavioral responses at a late stage. Collectively, this study provides state-of-the-art dynamic details of how attentional modulation gives rise to consciousness, while excluding confounding from early precursors and post-perceptual responses.

Top-down attention and attentional capture jointly promote visual consciousness

For each trial, a central stream (paired with a peripheral stream) presented a random sequence of four numbers (4/5/6/7) at a fast 10 Hz alternation rate (Fig. **1a**, **1b**). For the peripheral stream, a target image was temporally surrounded by two masks and two intervals between image and masks precisely manipulated to render the image (33ms duration) either visible (weakly masked, visible_image trials, VIS at Fig.**1b**) or invisible (heavily masked, invisible_image trials, INV at Fig.**1b**). For control trials designed to measure masks-evoked neural activity only, the image was replaced by a blank of same duration (visible_blank and invisible_blank trials, respectively).

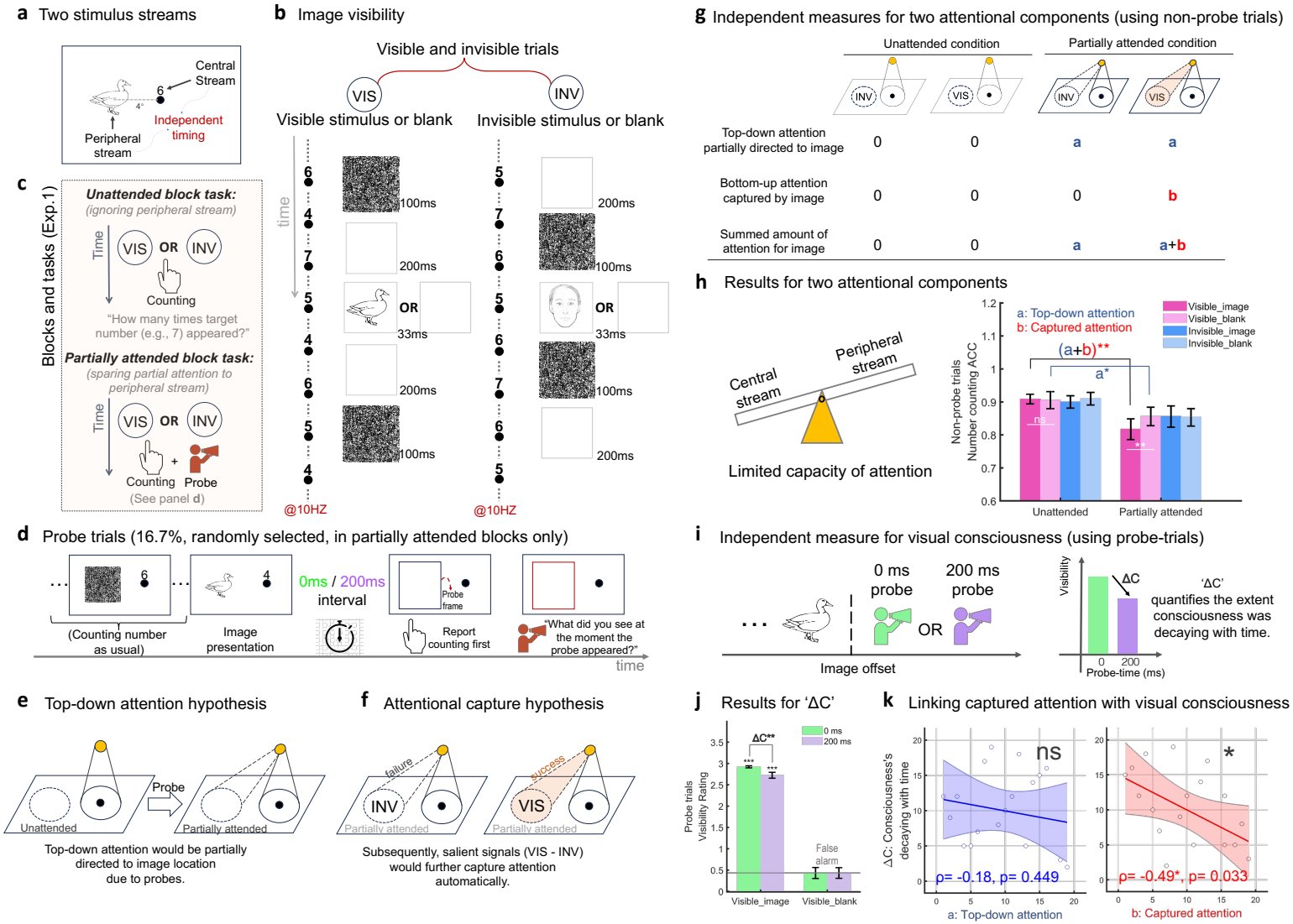

a Two stimulus streams
Central Stream
Independent timing
Peripheral stream
b Image visibility
Visible and invisible trials
VIS
INV
Visible stimulus or blank
Invisible stimulus or blank
100ms
200ms
OR
33ms
@10HZ
time
c
Blocks and tasks (Exp.1)
Unattended block task:
(ignoring peripheral stream)
Time
VIS OR INV
Counting
"How many times target number (e.g., 7) appeared?"
Partially attended block task:
(sparing partial attention to peripheral stream)
Counting Probe
(See panel d)
d Probe trials (16.7%, randomly selected, in partially attended blocks only)
0ms / 200ms interval
Probe frame
(Counting number as usual)
Image presentation
Report counting first
"What did you see at the moment the probe appeared?"
e Top-down attention hypothesis
Probe
Unattended
Partially attended
Top-down attention would be partially directed to image location due to probes.
f Attentional capture hypothesis
failure
success
Subsequently, salient signals (VIS - INV) would further capture attention automatically.
g Independent measures for two attentional components (using non-probe trials)
Unattended condition
Partially attended condition
Top-down attention partially directed to image
Bottom-up attention captured by image
Summed amount of attention for image
h Results for two attentional components
Central stream
Peripheral stream
Limited capacity of attention
a: Top-down attention
b: Captured attention
(a+b)**
a*
ns
Visible_image
Visible_blank
Invisible_image
Invisible_blank
Non-probe trials Number counting ACC
Unattended
Partially attended
i Independent measure for visual consciousness (using probe-trials)
0 ms probe
200 ms probe
OR
Image offset
Visibility
ΔC
'ΔC' quantifies the extent consciousness was decaying with time.
Probe-time (ms)
j Results for 'ΔC'
ΔC**
Probe trials Visibility Rating
False alarm
k Linking captured attention with visual consciousness
ΔC: Consciousness's decaying with time
ρ= -0.18, p= 0.449
ρ= -0.49*, p= 0.033
a: Top-down attention
b: Captured attention

Figure 1. Experimental paradigm and dissociation of attention's roles in visual consciousness. a, Schematic of central and peripheral stream. **b**, Illustration of visible and invisible image and control (blank) trials. **c**, Block and task design of attentional manipulation in Exp.1. **d**, Design of probe trials used in partially attended blocks. **e**, Schematic illustration showing occasional probes attract partial attention to peripheral stream. **f**, Schematic illustration showing visible rather than invisible images additionally capture attention in partially attended condition. **g**, Design and independent measures for top-down attention and captured attention using non-probe trials. **h**, Results for measures of two attentional components. **i**, Design and independent measure for visual consciousness using probe trials. **j**, Results for the measure of visual consciousness. Gray horizontal line illustrates false alarm level of visibility rating. **k**, Spearman correlation between one of two attentional components and visual consciousness. Rank values are plotted on each X- and Y- axis. ρ, spearman correlation coefficient. ns, non-significant; *, $p<0.05$; **, $p<0.01$; ***, $p<0.001$. The error bars represent the SEM.

We manipulated how much attention was allocated to the peripheral stream in two different blocks (unattended block and partially attended block, Fig.**1c**). In unattended blocks (Movie **S1**) that were conducted first, participants focused exclusively on the central stream to perform a high-demand counting task: before each block, they were informed of a fixed target number (e.g., 7), and at the end of each trial, they reported how many times this target appeared in the sequence. Counting performance was quantified as accuracy (i.e., ACC)—the percentage of trials where the reported count matched the actual number of target occurrences.

In partially attended blocks (Movie **S2**), we designed to direct partial top-down attention to peripheral stream. To achieve it, we introduced a probe for the peripheral image in 16% randomly selected trials (Fig.**1d**). Whenever seeing the probe cue, participants orally reported whether the image displayed at that moment was 'seen' and if yes, they needed to report details about its category and identity (audio recorded online and encoded offline by two encoders, Fig.**S1** and Methods). This made the image task-relevant and we hypothesized participants would allocate partial attention for the image to cope with probes. Since probe trials were determined randomly, we hypothesized top-down attention would be evenly allocated to peripheral stream even in non-probe trials (84% trials, Fig.**1e**, component **a** marked in Fig.**1g**). In this scenario, we further proposed salient signals in visible_image trials would additionally capture attention (**Fig.1f,** component **b** marked in Fig.**1g**) while non-salient signals in invisible_image or image absent trials (visible_blank and invisible_blank trials) would not capture attention. Since the capacity of attentional resources is limited (*42-44*), like the seesaw metaphor (**Fig.1h**, left panel) that if more attention is allocated to the peripheral stream, we proposed attentional competition may result in a deteriorated counting performance.

As a result, in unattended blocks (**Fig.1h**, right panel), we found that counting performance for the central stream was comparable across all four types of trials ($F_{(3,54)}=0.16$, $p=0.922$, $\eta_p^2=0.009$), suggesting visible images (relative to invisible images or image-absent blanks) failed to capture attention in unattended blocks where peripheral stream was being inhibited

while attention was directed to the central stream.

As expected, the contrast between partially attended blocks and unattended blocks ('attentional contrast' in short) revealed decreased counting performance (**Fig.1h**, right panel) for Invisible_image, Visible_blank and Invisible_blank trials when the target image was either invisible or absent. This decrease cannot be explained by block order effect (such as fatigue) because counting performance did not vary with block orders (unattended: $t_{(18)}$=-1.45, p=0.164, Cohen's d=0.33; partially attended: $F_{(9,162)}$=1.16, p=0.322, η_p^2=0.061). Critically, the attentional contrast for visible_image trials found a larger decrease than Visible_blank trials (interaction: $F_{(1,18)}$=6.82, p=0.018, η_p^2=0.275) and this decrease did not vary with image category ($F_{(2,36)}$=0.78, p=0.464, η_p^2=0.041). Since visible_image and visible_blank trials shared same timing structure, this decrease further suggests additional attention had been captured by visible images (i.e., component **b**).

Following the logic introduced above, we used the attentional contrast for visible_blank trials ($t_{(18)}$=-2.65, p=0.016, Cohen's d=0.61) to quantify the amount of top-down attention split for the peripheral stream (component **a**), and used the attentional contrast for visible_image trials ($t_{(18)}$=-3.62, p=0.002, Cohen's d=0.83) to quantify a summed component (i.e., component **a**+**b**): general top-down attention (component **a**) plus attention selectively captured by visible images (component **b**). Note that these two measures were calculated independently using different trials. By subtracting the component (**a**) from this independent summed component (**a**+**b**), we obtained a pure measure for component **b**.

To further examine which component contributes to visual consciousness, we also separated a clean measure of visual consciousness in the rest 16% probe trials, and planned to examine its correlation with these two attentional components. Specifically, as illustrated in **Fig.1i** (left panel), we presented the probe at two timepoints after image offset: one immediately after image offset (0ms) versus the other one delayed to 200ms post-stimulus offset. After image offset, we suppose its consciousness trace would decay with time (*45*). Thus, participants would likely report a higher visibility rating at 0ms than 200ms probes (**Fig.1i**, right panel). This decrease of visibility rating thus provides an independent measure (ΔC) to quantify how much visual consciousness decays with time.

We indeed found a higher visibility rating at 0ms than 200ms-delayed probes ($t_{(18)}$=3.02, p=0.007, Cohen's d=0.69; **Fig.1j**). Critically, this decay rate significantly correlated with the component **b** (captured attention, Spearman ρ=-0.49, p=0.033; **Fig. 1k** right panel), but not with the component **a** (top-down attention, ρ=-0.18, p=0.449; **Fig. 1k**, left panel). This correlation means that captured attention preserves conscious experience, slowing down its decay with time. Independent replication (Fig.**S2**) using a different sample of participants and different experimenter and audio encoders confirmed this finding.

Collectively, we conclude that top-down attention by itself cannot directly promote consciousness. Alternatively, it achieves so by initiating another mechanism, through which

salient stimuli capture attention. From this perspective, we suppose that the neural activities underlying this attentional capture process may contain NCC.

Neural Mechanism of Consciousness-related Attentional Capture: iEEG Evidence

Conceptualization

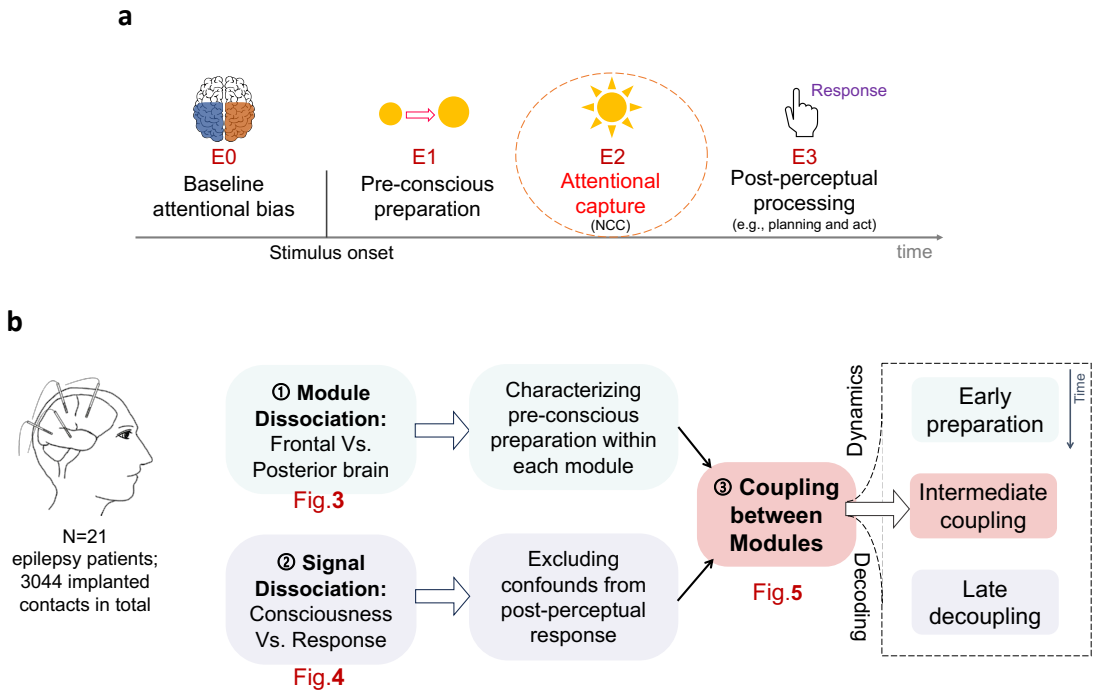


Figure 2. Conceptualizations and logic flow between three main sections of iEEG results. **a**, Conceptualization of a four-stage pipeline taking attentional capture process as the critical part containing neural correlates of consciousness (i.e., NCC). **b**. Logic flow between three main sections of iEEG results. Our primary goal was to isolate neural mechanisms of consciousness-related attentional capture process while excluding both pre-conscious and post-perceptual confounds.

It is important to notify that in Experiment 1 consciousness-related attentional capture only occurred when top-down attention was available (i.e., partially attended condition), but not when visual saliency signals were completely ignored. This dissociation suggests that top-down attention operates first to enable subsequent attentional capture, implying these are distinct processes separable along the time dimension.

Including these two attentional modulation processes, we proposed a four-stage pipeline of attention-induced changes, through which top-down attention promotes visual consciousness and enables subsequent goal-directed response. As illustrated in Fig.**2a**, this pipeline includes

first establishing pre-stimulus attentional bias (E0), then enhancing early visual saliency processing (E1), subsequently triggering consciousness-related attentional capture (E2, which directly promotes consciousness as we newly discovered in Exp.1), and finally initiating post-perceptual responses (E3, e.g., planning and act) for accurate image categorization. Combining a revised paradigm with high spatiotemporal-resolution iEEG recordings, our primary goal in Experiment 2 was to temporally discriminate consciousness-related E2 from its preparatory precursors (E0 and E1) and post-perceptual confounding (E3).

Distinct early preparations in the posterior versus frontal brain

In previous literature, evidences attributing the frontal brain as a critical module controlling attention (*28-31*) and the posterior brain as the other module initially representing visual sensory contents (*46, 47*) have been well-established using non-invasive methods (e.g., EEG and fMRI). Here, we used invasive iEEG data to delineate the distinct early preparatory processes elicited by attention within each module, each of which paves the way for the emergence of consciousness and related attentional capture.

Module-dependent early preparation: visual saliency detection

To maximize attention-induced early preparation, we modestly modified task of the paradigm in Exp.2. Specifically, we remained the unattended condition task roughly as same as Exp.1 (Movie **S3**), replicating the finding that unattended visible images failed to capture attention relative to invisible images (mean accuracy=0.777±0.032, $F_{(3,54)}$=0.95, p=0.424, η_p^2=0.050, Fig.**S3a**), but revised the partially attended condition task of Exp.1 to a fully attended condition task in Exp.2 (Movie **S4**). This task modification also improved feasibility and data quality in clinical settings. In this fully attended condition (hereafter termed 'attended condition' for short), participants were required to ignore the central number stream (see Methods) and perform an image categorization task at the end of each trial (animal/object/face, see Methods). As a result, the optimal categorization performance (accuracy = 0.937±0.017, chance level=0.333, $t_{(18)}$=35.41, p<0.001, Cohen's d=8.12, Fig.**S3b**) proved attention had been effectively directed to peripheral images under attended conditions.

Among 3,044 recorded contacts (1,900 in gray matter of cortical lobes), 847 contacts in sum were identified as responsive contacts (see Methods for details) whose activity significantly differed between visible vs. invisible trials (not confounded by horizontal or vertical eye gaze location, Fig.**S4)**. The Fig.**S5** illustrates an exemplary V1 responsive contact. Especially, in response to images displayed in the contralateral visual field, even under unattended conditions, this contact exhibited markedly stronger (400 μV vs. 40 μV, peak response amplitude detected at around 160ms, see Fig.**S5b** for more information) and more sustained (460 ms vs. 10 ms duration) responses to visible than invisible images (uncorrected p<0.001, cluster-based permutation corrected p<0.05). This V1 contact remained non-responsive for images displayed in the ipsilateral visual field.

Beyond V1, unattended visual saliency processing engaged broader posterior regions (Fig. **3a** and **Fig.S6**; Movie **S5**), including the occipital (O; 26.9%, 35 of 130 contacts), parietal (P; 16.0%, 62 of 387 contacts), and temporal (T; 6.1%, 51 of 838 contacts) lobes, as well as a lowest proportion of the frontal lobe (F, 2.9%, 16 of 545 contacts). Temporally, responses peaked between 200–400 ms before returning to chance levels at 600 ms.

By contrast, at attended conditions we observed a substantial expansion of responsive contacts. All four lobes exhibited increased responsiveness (Fig. **3a**), though most dramatically in the frontal lobe. Frontal contacts showed an over 12-fold increase compared to unattended conditions (from 2.9% to 36.5%). In striking contrast, the occipital lobe—specialized for lower-level visual processing—showed only a 2-fold increase (from 26.9% to 56.9%), and the fold-change increase for the posterior brain as a whole was significantly lower than that of the frontal brain (Fig. **3a**; $\chi^2(1) = 17.09$, $p < 0.0001$). This frontal–posterior divergence in attention-induced spatial expansion carries two implications. On the one hand, it supports the proposed role of the frontal brain as a specialized module for attentional control (*48-50*). On the other hand, it indicates that attention broadens the scope of information processing, from a predominantly posterior mode in the unattended state to a brain-wide mode.

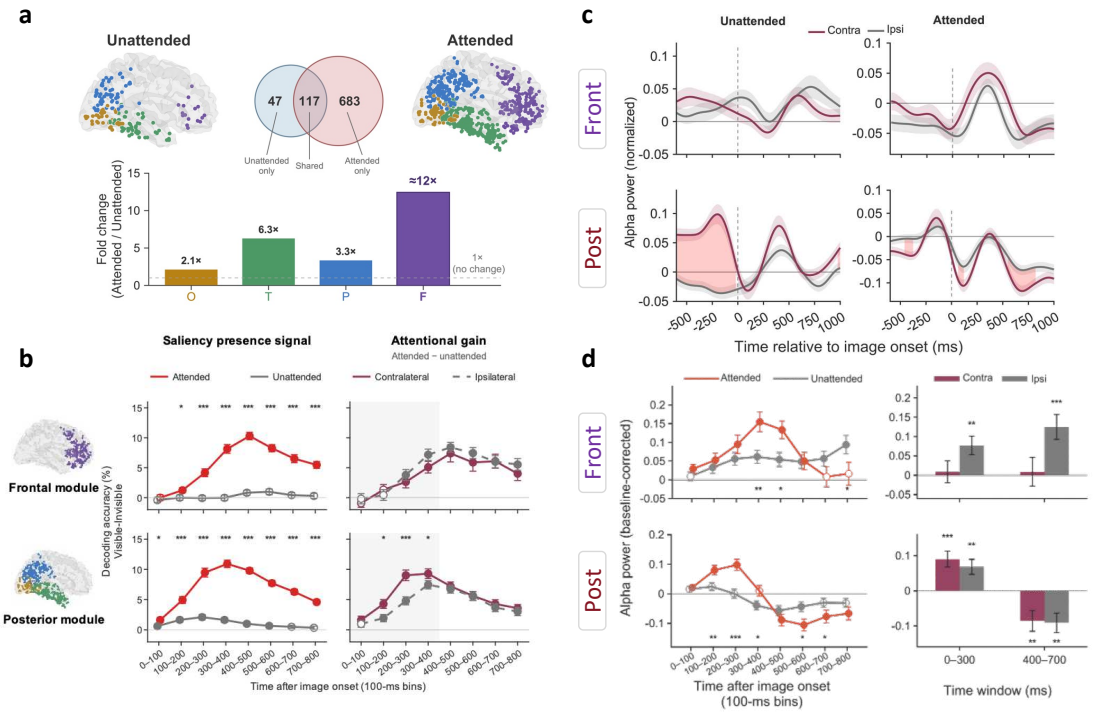


Figure 3. Module dissociation between frontal brain vs. posterior brain. a, Attention-induced increase on the number and distribution of responsive contacts, expanding most in the frontal brain. **b**, Module dissociation in terms of saliency presence signal and its attentional gain. Contralateral vs. ipsilateral responses were compared for the posterior brain (lower panels) and the frontal brain (upper panels). **c**, Module dissociation in pre-stimulus alpha-band power. Alpha-band power was compared between contralateral vs. ipsilateral hemispheres of the

frontal brain (upper panels) and the posterior brain (lower panels), under unattended (left panels) and attended conditions (right panels), respectively. The dotted line indicates image onset. Shaded area around lines represents SEM. Shaded area between lines indicates significant difference between two hemispheres (cluster-based permutation corrected $p<0.05$). Results for visible trials were reported here (See Fig.**S8** for invisible trials). **d**, Module dissociation in saliency-evoked alpha-band power. Baseline correction was performed on alpha-band power. The corrected alpha-band power in the attended condition was compared with that in unattended condition (left column). Under attended conditions, the contralateral vs. ipsilateral responses were further compared across an early and a late time window (right column). For panels **b** and **d**, filled circles indicate significant difference versus 0 (FDR corrected $p<0.05$) while asterisks indicate significant difference between legend conditions. *, uncorrected p<0.05; **, uncorrected p<0.01; ***, uncorrected p<0.001. 'Front' represents the frontal module; 'Post' represents the posterior module. Without otherwise denoted, all X-axis tick labels represent time relative to image onset, in unit of millisecond (ms). The error bars represent the SEM.

In the attended condition, when both modules were active, we compared their sensitivity to detect saliency presence signals. For each combined condition of visibility (visible/invisible) and attention (attended/unattended), multivariate SVM models were first trained to decode binary presence (present/absent) of visual images (also see **Method**-iEEG: decoding analysis). Then, using the resulting decoding accuracy measures, a visual saliency contrast (i.e., visible-invisible) was further performed to quantify the amplitude of saliency presence signal for each attended and unattended condition. Larger amplitude indicates higher sensitivity to detect presence of visual saliency stimuli. Not surprisingly, we found the frontal brain exhibited a consistent 100ms delay relative to the posterior brain under the attended condition (Fig.**S7**), implying it receives feedforward signals from the posterior brain (*23, 51*).

To quantify attention-induced increase (i.e., attentional gain) upon saliency presence signals, we performed a contrast between attended versus unattended conditions. In the posterior brain, top-down attention significantly enhanced saliency presence signals starting from within the first 100ms (Fig. **3b** lower-left panel, bin 1, $t_{(118)}=2.34$, $p=0.021$, Cohen's d=0.21), providing empirical support for the conceptualization of early sensory enhancement (stage E1, Fig. **2a**) caused by top-down attention (also see (*11, 12*)). By contrast, in the frontal brain, top-down attention significantly enhanced saliency presence signals till to the second bin (100-200ms bin, Fig. **3b** upper-left panel).

To evaluate whether attentional gain on saliency presence signals are constrained by the contralateral hemisphere lateralization biases of visual propagation(*52*), we further performed a contrast between contralateral versus ipsilateral response. As revealed, posterior brain attentional gain measures exhibited lateralization bias that was most pronounced during the rising phase (bins 1-4, Fig.**3b**, Lateralization: $F_{(1,98)}=4.20$, $p=0.043$, $\eta_p^2=0.041$; Phase: $F_{(1,98)}=0.04$, $p=0.844$, $\eta_p^2=0.0004$; Interaction: $F_{(1,98)}=3.64$, $p=0.059$, $\eta_p^2=0.036$) and became non-significant in the later falling phase (bins 5-8, $t_{(98)}=0.62$, $p=0.535$). By contrast, in the frontal brain we did not observe significant attentional gain for each bin (Fig. **3b**, upper-right

panel, bins 1-8: *ps*>0.436). Together, this attention-induced delayed yet bilaterally integrated response profile demonstrates that attention induces different early preparation in the frontal brain, that it does not merely extend visual sensory processing of images but constitutes a higher-order integrative module that synthesizes feedforward signals from both posterior hemispheres (*53*).

Module-dependent early preparation: attention-related alpha-band activity

Given evidences above illustrating **distinct early preparations in the posterior versus frontal brain** about visual saliency detection, we next examined this issue using measures relevant to attentional control. Specifically, we focused on analyzing alpha-band activity, a classical marker on this issue (*54-57*). For example, it is well known that suppressing peripheral distractors would shift the inhibitory alpha-band power towards the contralateral hemisphere which initially processes these distractors. Consistent with this view, in unattended conditions (Fig.**3c** for visible trials, Fig.**S8** for invisible trials), we observed robust pre-stimulus alpha power lateralization toward the contralateral hemisphere in the posterior brain (Fig.**3c**, lower left panel, Unattended).

Strikingly, attended conditions induced a complete reversal of this alpha lateralization pattern. Alpha power now lateralized toward the ipsilateral hemisphere (Fig. **3c**, lower right panel, Attended), effectively inhibiting the ipsilateral hemisphere while disinhibiting the contralateral hemisphere in preparation for upcoming stimuli. This attention-driven reversal of posterior alpha activity demonstrates how top-down attention dynamically reconfigures the posterior brain processing according to task demands.

In contrast, the frontal brain showed no significant pre-stimulus inter-hemispheric alpha bias under either attended or unattended conditions (Fig. **3c**, upper panels). This functional dissociation provides additional evidence for the hierarchical architecture view: the posterior brain acts as a lower-order module where alpha-band activity reflects the spatial focus of attention in a retinotopic manner, while the frontal brain operates as a higher-order integrative module that is not constrained by this retinotopic organization.

Beyond pre-stimulus attentional biases, the functional dissociation between frontal and posterior brain regions further manifested in post-stimulus saliency-evoked alpha-band activity under attended conditions (Fig.**3d**). Klimesch's two-stage framework (*58*) proposes that top-down attention engages alpha oscillations to access stored knowledge through sequential processes: an initial alpha power increase suppresses task-irrelevant neural activity (noise reduction), enabling salient signals to pop-out from background activity—followed by a subsequent alpha power decrease that further amplifies the processing of these prioritized signals.

Consistent with this two-stage framework, we observed a biphasic increase-decrease pattern in posterior alpha-band activity (Fig. **3d**, lower panels, Posterior brain): an initial power increase

(peaking at ~250 ms; suppression phase), followed by a significant decrease (troughing at ~550 ms; facilitation phase). Crucially, the magnitude of this biphasic modulation (peak-to-trough alpha amplitude change) positively correlated with the strength of saliency category representation—quantified as mean saliency category decoding accuracy—across posterior brain regions (Fig.**S9**). These findings provide direct support for Klimesch's two-stage framework that top-down attention orchestrates sequential alpha dynamics to access stored sensory knowledge in the posterior brain.

In sharp contrast, stimulus-evoked alpha activity in the frontal brain exhibited fundamentally distinct dynamics. Critically, no biphasic modulation was observed. Instead, we identified sustained alpha lateralization toward the ipsilateral frontal hemisphere (Fig. **3d**, upper panels). It is proposed that frontal hemispheres compete for attentional control through mutual inhibition (*59, 60*), with each hemisphere able to direct attention toward its contralateral hemifield. Therefore, the lateralized alpha activity indicates that the ipsilateral frontal lobe was continuously suppressed, thus likely stabilizing attention towards where the salient signal appears. Collectively, such divergence between posterior alpha dynamics (phasic increase-decrease transitions) and frontal alpha dynamics (tonic interhemispheric lateralization) sheds light on their complementary early preparation with regard to attentional control.

Signal dissociation discriminates consciousness from post-perceptual response

Discriminating post-perceptual response from earlier-initiated conscious experience is a fundamental challenge in consciousness research (*39, 61*).

In this section, we tackle this issue from a new perspective. At first, we suppose neural signals tracking emergence/presence of perceptual consciousness and signals tracking perceptual contents are intrinsically different (Fig.**4a**, Prediction 1). Although these signals have been shown to diverge in multiple domains (e.g., visual perception (*62-64*) and action control (*65*)), previous consciousness research has typically investigated them in isolation—examining either presence (e.g., (*66, 67*)) or content (e.g., (*68*)) signals separately—without directly examining which signal best tracts conscious experience. Second, we predicted that the presence signals would continue to decline during late fading of conscious experience, while categorical content signals might be maintained or even rebound to support category-dependent post-perceptual responses (Fig.**4a**, Prediction 2). Note that a 1000-ms freezing window had been set for participants to wait after image offset before initiating their key-press response (Methods).

To test these two signal dissociation predictions, we adopted the same quantification method for the saliency category signal, with the only modification being that the SVM models were now trained to discriminate image categories (animal/object/face) instead of image presence (see Methods for further details).

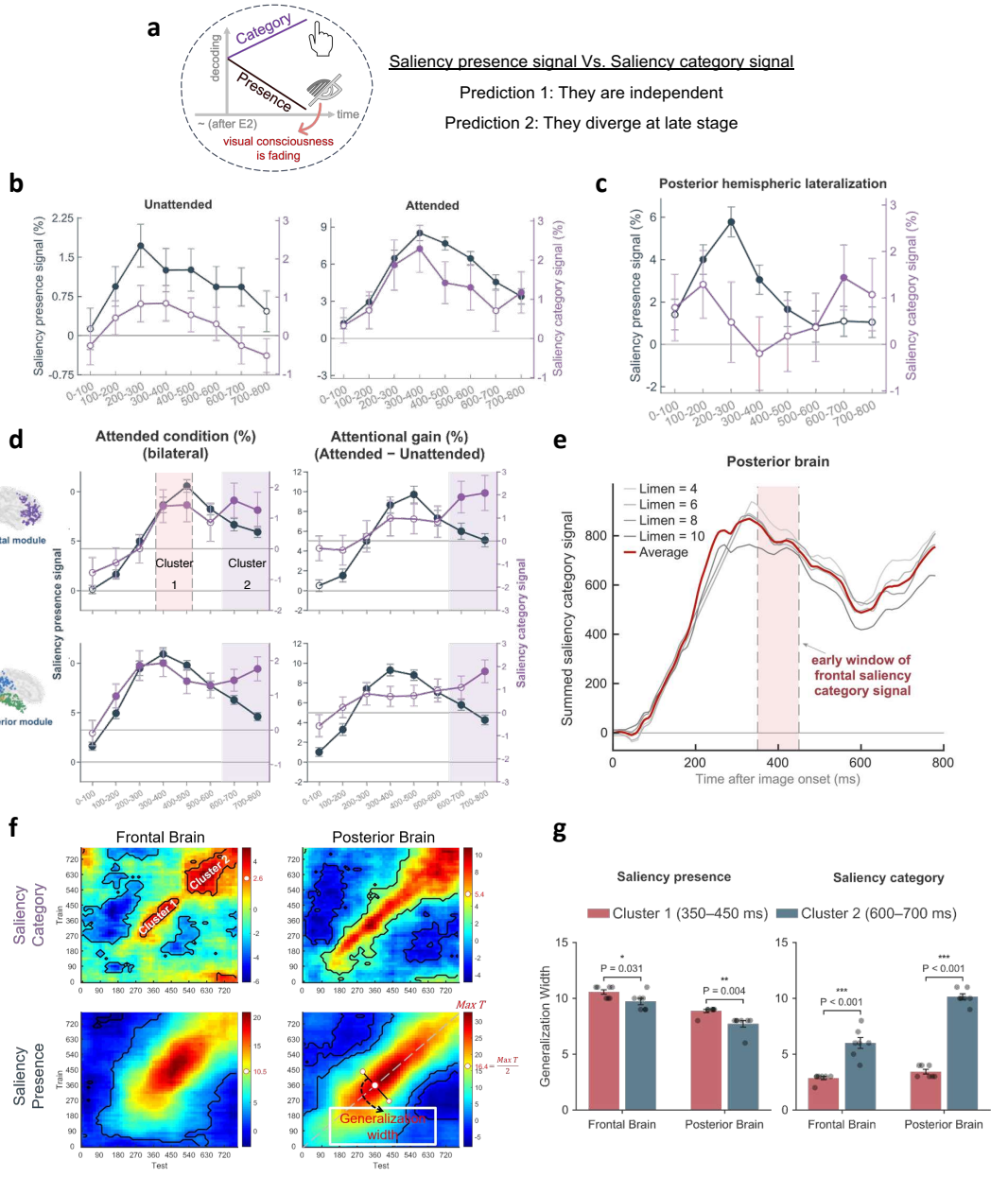


Figure 4. Signal dissociation between saliency presence versus saliency category signals. **a,** Working predictions about signal dissociation. **b**, Two-Yaxes plot for two saliency signals of ipsilateral hemisphere of the posterior brain under unattended (left) and attended (right) conditions. **c**, Signal dissociation on hemisphere lateralization index (contralateral-ipsilateral) of the posterior brain. **d**, Signal-dissociation in the frontal brain (upper row) and the posterior brain (lower row) in terms of bilateral mean saliency signal intensity (left column) and their attentional gain (right column). Purple-shaded areas highlight their divergence at late stage (>600ms). Before that, the pink-shaded area at the upper-left panel marks the early window (cluster 1) of frontal brain saliency category signal. **e**, Time course of summed saliency category signal of the posterior brain. Shaded area indicates the early window of saliency category signal of the frontal brain. For each gray curve, an inclusion criterion (i.e., Limen) quantifies how many percentages above zero a contact could be included to calculate the summation. The red

curve represents the mean summation averaged across four individual gray curves. **f**, Temporal generalization analysis under attended conditions for saliency category signals (upper row) and saliency presence signals (lower row) of the frontal brain (left column) and the posterior brain (right column), respectively. Warm-colored clusters represent significant generalization (FDR corrected p<0.05). Analysis on saliency category signals of the frontal brain revealed two discrete clusters. A generalization width index (marked by a line-segment in the bottom-right panel, see main text for more information) was calculated for each timepoint along the diagonal line. **g**, Generalization width compared between these two clusters for each combined condition of frontal/posterior brain (columns) and category/presence signals (rows). Each scattered point on the bar represents an individual diagonal time point within each legend cluster. Except for otherwise denoted, filled circles indicate significant difference versus 0 (FDR corrected p<0.05; corrected p>0.05 for empty symbols), asterisks along X-axis indicate significant difference between legend conditions (uncorrected p<0.05). Without otherwise denoted, all X-axis tick labels represent time relative to image onset, in unit of ms. The error bars represent the SEM.

Signal dissociation: Cross-hemisphere projection

We started to test for Prediction 1 of the signal-dissociation hypothesis by testing whether saliency category signals propagate concurrently with saliency presence signals during cross-hemisphere projection. First of all, we found the contralateral hemisphere response can expectedly encode both saliency presence and saliency category signals irrespective of under attended or unattended conditions (Fig.**S10**). The real question lies in the ipsilateral hemisphere response, that whether this ipsilateral response could also encode saliency presence and saliency category signals concurrently.

Under unattended conditions (Fig. **4b**, left, Unattended), ipsilateral responses only encoded saliency presence signals (light blue curve, bins 2-7, FDR corrected p < 0.05) but failed for saliency category signals (light purple curve, all bins, p > 0.069, FDR corrected p>0.1). Under attended conditions, however, ipsilateral responses encoded both two signals (Fig. **4b**, right, Attended; FDR-corrected p < 0.05). This dissociation reveals that cross-hemisphere propagation of saliency category signals requires attention, whereas saliency presence signals could transfer between hemispheres without being constrained by attentional demand.

Then, we computed a lateralization index (contralateral – ipsilateral) to further examine whether these two signals both follow contralateralization bias (i.e., contralateral>ipsilateral). Under the attended condition, saliency presence signals expectedly exhibited stronger contralateral hemisphere response (Fig.**4c**, bins 2-5, FDR corrected p<0.05), whereas saliency category signals showed a non-significant lateralization bias during early processing (bins 1–2: p = 0.270 and 0.080, respectively; Fig. **4c**). At bin 3—when saliency presence signals peaked in lateralization index (max lateralization, $t_{(104)}$= 8.19, p <0.001)—saliency category signals remained bilaterally symmetric ($t_{(104)}$= 0.55, p = 0.586). Conversely, at bin 7 (600-700ms)—as saliency presence signals became bilateral (lateralization nonsignificant: $t_{(104)}$= 1.54, p =

0.126)—saliency category signals developed significant contralateral bias ($t_{(104)}$= 2.06, p = 0.042).

Collectively, saliency category signals deviate fundamentally from saliency presence signals in three aspects-They require attention to complete cross-hemisphere projection, are more symmetric between hemispheres within the first 600ms, and exhibit significant contralateral hemisphere bias till to late stage (>600ms).

Signal dissociation: post-perceptual global late content retrieval

We now tested for Prediction 2 of signal dissociation, that saliency category signals would diverge from saliency presence signals at the late stage. In the posterior brain, we found saliency presence signals and saliency category signals followed similar trajectories before 600ms (Fig.**4d**, lower-left panel, bins 2-6). After 600ms (bins 7-8), however, saliency presence signals continued declining while saliency category signals rebounded, showing expected late signal dissociation. Similarly, attentional gain analysis for the posterior brain (Fig.**4d**, lower-right panel) again demonstrated an inverted U-shaped profile for saliency presence signals, and a temporally climbing profile of attentional gain for saliency category signals, gaining most during late bins.

In the frontal brain, the saliency presence signal (Fig.**4d**, upper-left panel) and its attentional gain (Fig.**4d**, upper-right panel) both exhibited an inverted U-shaped profile (light blue curve) too. And, the saliency category signal and its attentional gain were still mostly pronounced during the late stage (light purple curve, late bins 7-8, FDR corrected $p<0.05$). Collectively, we found the late signal dissociation occurred in both the posterior brain and the frontal brain, suggesting this late process is expanding globally. For this reason, we term this process as 'global late content retrieval'.

It is important to note that in the frontal brain we observed significant saliency category signal appearing till to bins 4-5 (Cluster 1, Fig.**4d**, upper-left panel, light purple curve, FDR corrected $p<0.05$; see Fig.**S11** for more fine-grained time course), later than that in the posterior brain. When and how the frontal brain encodes consciousness content are of special significance in inferring mechanism of consciousness (*2, 26, 27, 69*). An influential globalist view proposes the frontal brain can broadcast conscious content stream to widely distributed posterior regions. If true, then, the total amount of content representations in the posterior brain should be significantly enriched immediately after the frontal brain starts broadcasting. However, as revealed, we instead found a general decrease during and following this early cluster 1 of frontal content representations (Fig.**4e**).

To further examine whether the neural representations of these two frontal category clusters could generalize to each other, we conducted a temporal generalization analysis for each signal and brain region (Fig.**4f**). This analysis evaluates to what extent neural patterns at one timepoint can generalize to other timepoints, yielding a 2D generalization map (train time by test time) of

T-values. As shown in the upper-left panel , this analysis again revealed two discrete clusters (Cluster 1 and 2) of category signals in the frontal brain. Evolving along the diagonal, these two clusters failed to generalize to each other—indicating that they had developed into distinct neural patterns.

Within the generalization map, notably, the later Cluster 2 appeared more expanded than the earlier Cluster 1 in the direction perpendicular to the diagonal line. To verify this possibility, a generalization width index was calculated in this direction. As represented by the black line segment marked in the lower-right panel of Fig. **4f**, this index measures the distance between two threshold points (small circles, face-colored in white and line-colored in red). The threshold was set to half of the maximum generalization T value over all timepoints; thus, the length of the line segment measures the temporal duration of supra-threshold generalization and could be compared between cluster 1 and 2. To exclude artificial effect of cluster size, we cropped these two clusters into same length to run following tests (Fig.**4g**; Cluster 1: 350–450 ms; Cluster 2: 600–700 ms).

Compared with Cluster 1, generalization width during Cluster 2 sharply contracted for saliency presence signals (Fig. **4g**, left panel)—becoming significantly narrower than that in Cluster 1 for both the frontal brain ($t_{(12)}$=-2.45, p=0.031, Cohen's d=1.31) and the posterior brain ($t_{(12)}$=-3.58, p=0.004, Cohen's d=1.91). That means during the late stage the temporal sustainability of saliency presence signals was declining globally.

For saliency category signals (Fig. **4g**, right panel), however, Cluster 2 exhibited a significantly broader generalization width in the frontal brain ($t_{(12)}$ = 6.18, p <0.001, Cohen's d = 3.30). Same analysis revealed similar dynamics in the posterior brain: the Cluster 2 also exhibited a significantly broader generalization width than Cluster 1 ($t_{(12)}$ = 20.35, p <0.001, Cohen's d = 10.88), replicating the late expansion effect. Collectively, these results demonstrate that the late generalization width expansion of category signals is a global phenomenon—occurring robustly in both the frontal and posterior cortices.

Collectively, findings above provide converging evidences for the predicted dissociation between the two signals. Among them, it is the saliency presence signal and its attentional gain (alike with an inverted U-shaped profile) that best track attention-induced promotion upon visual consciousness–its explicit emergence, maintenance and fading–within hundreds of milliseconds. On the contrary, the saliency category signal and its attentional gain might best fit task-relevant post-perceptual responses. In the dimension of time, above findings illustrate that the late post-perceptual response in our paradigm started around 600ms post-stimulus onset, suggesting visual consciousness must have emerged and have been facilitated by attentional capture before this cutting-edge timepoint.

Functional coupling between attention module and sensory content module

Based on findings of module dissociation and signal dissociation reported in above two iEEG sections, here we further proceed to examine whether top-down attention expectedly induced functional coupling between these two modules, and how this frontal-posterior coupling evolved across time. As a test, we predicted that this frontal-posterior coupling would be selectively established under attended conditions (Note that Exp.1 shows that attentional capture cannot occur in the unattended condition, Fig.**1h**), and its temporal profile would successively mirror three post-stimulus stages (Fig.**2a**)—early preparation (E1, prediction of no coupling), intermediate conscious emergence (E2, prediction of positive frontal-posterior coupling), and late fading (E3, prediction of vanishment of frontal-posterior coupling) of visual consciousness. Findings about signal-dissociation further motivated us to examine whether the targeted frontal-posterior coupling patterns encode saliency presence and/or saliency category signals.

Practically, we quantified pairwise functional connectivity between responsive contacts in the 4Hz-centered theta band (3-5Hz, using 300ms window with 100ms step, see Methods). Positive values indicate saliency-evoked coupling (i.e., visible>invisible), while negative values reflect decoupling (i.e., visible<invisible). This 4Hz-centered theta band frequency range was selected because: (1) our spectral analysis confirmed this band showed the strongest saliency-evoked coupling under both attended and unattended conditions (Fig.**S12**), and (2) theta oscillations are known to mediate inter-cortical synchronization and communication (*49, 70, 71*).

As shown in Fig.**5a**, multiple contact pairs were averaged into one electrode pair to control for data homogeneity. All coherence-related statistics were thus performed on electrode pair level. To evaluate coherence-related activity intra-between each module and inter-between two modules, we further grouped 9 lobe pairs into 3 groups (Fig.**5b**)– Posterior group (including OO, OP, OT, TT, TP and PP), Frontal group (FF only) and Frontal-Posterior group (FP and FT).

Averaged across all electrode pairs, the profile of saliency-evoked theta coherence dynamics revealed three distinct stages under attended conditions (Fig. **5c**, red line): (1) an early stage of overall null-coherence (bin 1: $t_{(925)}$=-0.22, p=0.826), (2) an intermediate stage of overall coupling (positive coherence value, bins 2-4: FDR corrected p<0.001), and (3) a late stage of overall decoupling (negative coherence value, bins 5-6: FDR corrected p<0.003) – corresponding well to our conceptual framework (E1-E3, Fig.**2a**). Next, we focus on clarifying how these module-specific and inter-module coherence patterns evolve across the early, intermediate and late stages, respectively.

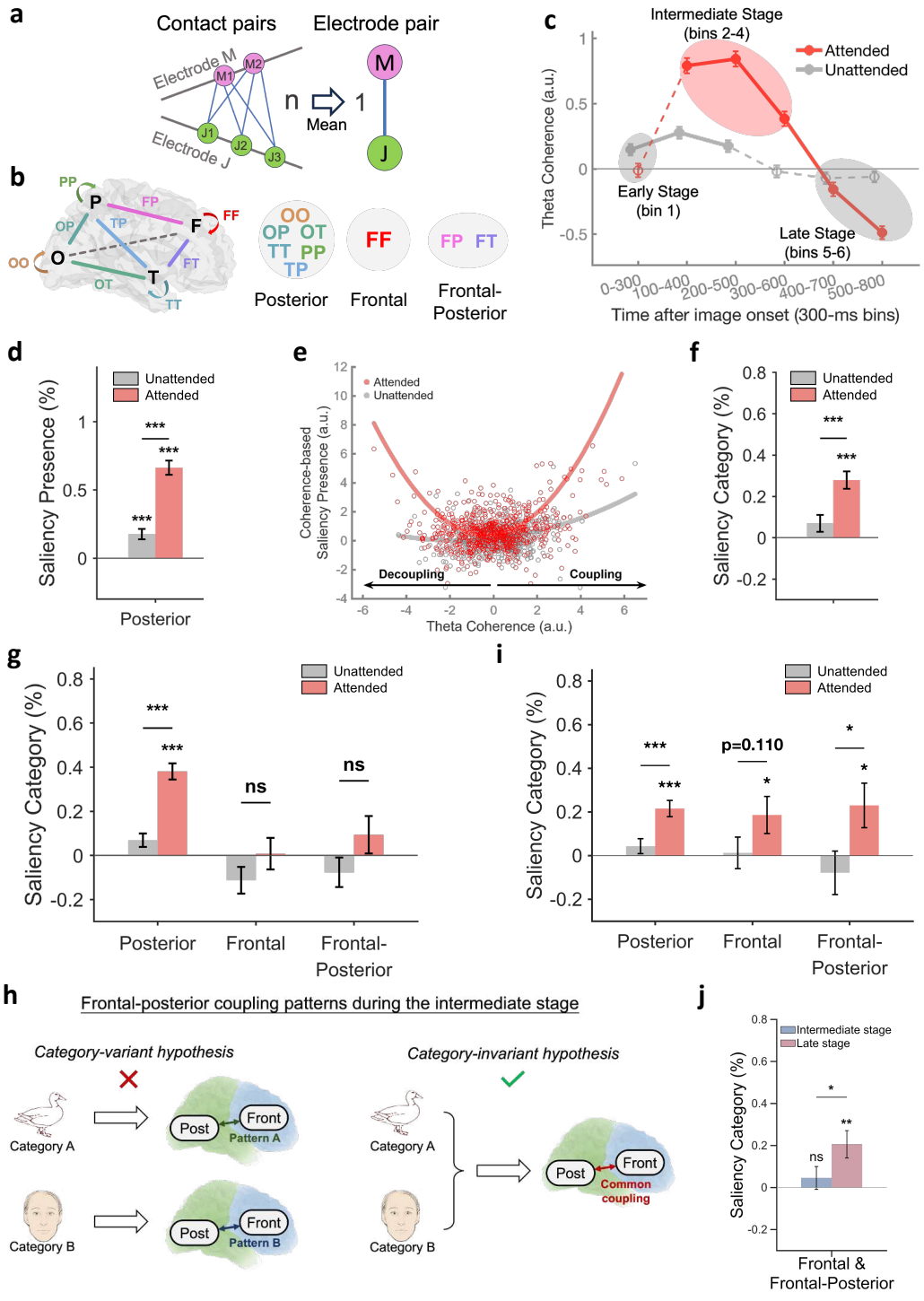


Figure 5. Attention-induced coupling between two modules. a, Multiple contact pairs were averaged into one electrode pair to control for data homogeneity. **b**, Graphical illustration of 9 cortical lobe pairs grouped into 3 module groups. **c**, Time course of mean theta coherence averaged across all electrode pairs. Under attended conditions (red line), three stages including an early stage, an intermediate stage and a late stage were identified. **d**, Coherence-based saliency presence decoding results for the posterior brain at the early stage. **e**, Attention-induced coupling-and-decoupling reorganization evidenced by U-shape function modelling between coherence-based saliency presence decoding and saliency-evoked theta coherence. Each circle

represents a lobe-electrode pair unit within the posterior brain under attended (red) or unattended (gray) conditions. **f**, Coherence-based saliency category decoding results for the posterior brain at the early stage. **g**, Coherence-based saliency category decoding results for three groups at the intermediate stage. **h**, Schematic illustration for two opposing hypotheses about frontal-posterior coupling patterns at the intermediate stage, with the category-invariant hypothesis empirically validated by our data. Achromatic line-draw images are colored to enhance visibility. **i**, Coherence-based saliency category decoding results for three groups at the late stage. **j**, Coherence-based late content retrieval under attended condition. This retrieval was evidenced by increase of saliency category signal averaged across the Frontal and Frontal-Posterior groups. +, $p<0.1$; *, $p<0.05$; **, $p<0.01$; ***, $p<0.001$. The error bars represent the SEM.

Early preparation in the posterior brain

At the early stage, to understand how top-down attention prepares for subsequent attentional capture, we first investigated how the saliency-evoked theta coherence values were modulated by attention. We found that, by average, the saliency-evoked coherence was significantly above zero (i.e., coupling) in the unattended condition (gray circle at bin 1, Fig.**5c**). However, in the attended condition the mean coherence was at zero-level (red circle at bin 1, Fig.**5c**), exhibiting a significant decrease relative to that under unattended conditions ($t_{(925)}$=-2.40, FDR corrected p=0.017).

However, when we imported these trial-wise coherence values into SVM models to decode for image presence (present/absent) at the posterior brain, we revealed significant saliency presence signal at the attended condition (i.e., higher decoding accuracy for visible than invisible trials), stronger than that at the unattended condition (Fig.**5d**, p<0.001). These results suggest posterior coherence patterns were in fact significantly altered by attention, resulting in more sensitive visual saliency detection at the early stage.

We thus modelled the relationship how saliency presence signals varied as a function of saliency-evoked coherence values. As a result, we revealed a U-shaped pattern between these two measures (Fig.**5e**, red curve; see Fig.**S13** for a more rigorous 'two-line' test for this relationship), demonstrating that top-down attention had coupled some pairs (i.e., positive coupling) while simultaneously decoupled some other pairs (i.e., negative decoupling). Thus, their cancelling out each other might have led to an averaged zero-level mean coherence value. Importantly, this U-shaped pattern was present under attended conditions only and absent under unattended conditions (Fig.**5e**, gray curve), suggesting that top-down attention induced active reorganization of coupling and decoupling patterns during early visual saliency processing at the posterior brain.

It is natural to propose that this active reorganization might allow stimulus-specific signals pop-out from background noise, thus resulting in category-specific coherence patterns for individual electrode pairs. We tested this hypothesis by importing coherence values into SVM models to

decode for image category (animal/object/face). The results confirmed our prediction, revealing significant saliency category signal in the attended condition (visible>invisible, $t_{(651)}$=6.59, p<0.001), and this signal intensity was significantly stronger than that in the unattended condition ($t_{(651)}$=3.54, p<0.001, Fig.**5f**).

Intermediate frontal-posterior coupling

During the intermediate stage (bins 2-4, Fig. **5c**), same analyses on theta coherence values revealed saliency-evoked global coupling (i.e., coherence>0) under attended condition, as well as a general significant increase relative to unattended condition (all ps<0.001). This coupling effect slightly differed between three groups (Fig.**S14**, also see Fig.**S15** and **S16** for information about each lobe pair). More specifically, for the Posterior group and the Frontal group, their attentional gain is a quantitative elevation from weak coupling to stronger coupling, whereas for the Frontal-Posterior group its attentional gain is a qualitative change shifting from no coupling state to coupling state.

Coherence-based decoding analysis revealed significant decoding for both saliency presence signal and saliency category signal under the attended condition intra-between the posterior brain (Fig.**5g**, Posterior group, red bar), as well as significant attentional gain relative to the unattended condition (Fig.**5g**, Posterior group, difference between red and gray bars). In this scenario, one critical question remains open when these two modules get coupling with each other during this intermediate stage: do frontal-posterior coupling patterns differ between categorical contents? As shown in Fig.**5h**, a category-variant hypothesis (left) and a category-invariant hypothesis (right) await empirical testing.

For the Frontal group and the Frontal-Posterior group, however, coherence-based decoding analyses revealed non-significant saliency category signal (Fig.**5g**, Frontal group, $t_{(188)}$=0.11, p=0.911; Frontal-Posterior group, $t_{(146)}$=1.10, p=0.273) and non-significant attentional gain for saliency category signal (Frontal group, $t_{(188)}$=1.336, p=0.183; Frontal-Posterior group, $t_{(146)}$=1.477, p=0.142). On the contrary, the Frontal group and the Frontal-Posterior group demonstrated significant decoding and significant attentional gain for saliency presence signals, only (Frontal: $t_{(188)}$>4.43, p<0.001; Frontal-Posterior: $t_{(146)}$>4.11, p<0.001; Fig.**S14**).

As an additional test, for each group, we imported coherence values of each single patient's all electrode pairs (after controlling for data homogeneity, see Fig.**5a**) to train decoding models. This subject-wise multivariate decoding analysis provides an additional test to more rigorously evaluate whether the multivariate coherence pattern varied with saliency category at the intermediate stage.

Replicating above findings, results of subject-wise multivariate decoding analysis (Fig.**S17**) further confirmed that the Frontal group and the Frontal-Posterior group could only encode saliency presence signals (Frontal: $t_{(9)}$=2.119, p=0.065; Frontal-Posterior: $t_{(12)}$=3.65, p=0.003)，

but could not for saliency category signals (Frontal: $t_{(9)}$=1.62, p=0.139; Frontal-Posterior: $t_{(12)}$=-1.08, p=0.300) at the intermediate stage.

Collectively, these results provide empirical support for the 'content-invariant hypothesis' (Fig.**5h**). That is, when these two modules get coupling with each other during this intermediate stage, a common coupling mechanism generally couples the two modules regardless of categorical contents of conscious experience.

Late decoupling

No conscious experience persists indefinitely. Results at the late stage align well with this fading of visual consciousness. As shown in Fig.**5c,** the overall theta coherence at late stage exhibited sharp decrease (decoupling) relative to the intermediate stage under attended conditions. This decoupling differed between three groups. More specifically, as shown in Fig.**S14**, the Posterior group decreased from positive coupling to negative decoupling, while the Frontal group and Frontal-Posterior group decreased from positive coupling to zero level.

Despite of these late decoupling effects, the decoupled patterns differ between categories. Especially, for both the Frontal group and the Frontal-Posterior group who failed to encode saliency category at the intermediate stage, we found they each (Fig.**5i**) and their union (Fig.**5j**) exhibited significant saliency category signal at the late stage ($t_{(335)}$=3.16, p=0.002). And, more importantly, the contrast between late vs. intermediate stages revealed a significant increase for saliency category signal ($t_{(335)}$=2.15, p=0.032, Fig.**5j**), further providing coherence-based evidence for the post-perceptual process of late content retrieval (Fig.**4d**).

General Discussion

This article investigates how top-down attention promotes visual consciousness. We first isolated top-down attention and captured attention using a novel psychophysical paradigm, establishing a specific correlation between captured attention and consciousness. Then, using iEEG data, we confirmed functional dissociation between the frontal brain (attention module) and the posterior brain (sensory module), and revealed that the coherence between the two modules (i.e., frontal-posterior coupling) dynamically mirrored early preconscious preparation, intermediate conscious promotion and late fading of explicit visual consciousness in the dimension of time. At early preparation stage, top-down attention modulated alpha band activity and decoupled the whole brain to facilitate detection and categorical discrimination of visual saliency signal. During the intermediate stage, these two modules got functionally coupled with each other but the pattern of frontal-posterior coupling simply changed in response to saliency presence but did not vary with categorical contents. At late stage, the coupling between two modules became disentangled via a category-dependent decoupling process. Together, we conclude that top-down attention prepares for consciousness first, and then promotes visual consciousness via mediation of a category-invariant, binary frontal-posterior coupling mechanism in the human brain.

Separating Pre-conscious Vs. Conscious activity

Our psychophysical finding that top-down attention promotes visual consciousness indirectly by mediation of attentional capture process represents a significant advance. It implies top-down attention cannot directly translate into visual consciousness, but makes necessary preconscious preparation for consciousness arising. Existing research has extensively documented attention-induced neural modifications (*11, 48-50, 58, 71-82*). Especially, this neural enhancement effect starts early in time, within the first 100ms post stimulus-onset, and expands broadly in space, from early visual areas (LGN/V1) to widely distributed regions of the posterior brain (*11, 12*). Psychophysical findings here suggest these early neural enhancement effect might best prepare for subsequent consciousness-related attentional capture, allowing salient signals pop out from background noise, but not necessarily serve for consciousness per se.

Our iEEG results additionally show such preconscious preparation starts prior to visual stimulus onset. Pre-stimulus alpha-band power lateralization across posterior hemispheres directly reflects this preparatory attentional modulation. In unattended trials, top-down attention elicited inhibitory alpha oscillations biased toward the visual-input-receiving contralateral hemisphere of the posterior brain (Fig.**3c**), which aligns with prior evidence (*54, 55*). Such hemispherically lateralized alpha oscillations function to suppress task-irrelevant peripheral images and resist attentional distraction (*55-57*). Conversely, this interhemispheric alpha lateralization pattern reversed under attended conditions, facilitating peripheral image processing via disinhibiting the visual-input-receiving hemisphere. This transition from unattended suppression to attended facilitation reveals how top-down attention reconfigures neural states of bilateral posterior hemispheres to prepare for the incoming stimulus.

This preconscious preparation lasts till to roughly 250ms post-stimulus onset. In bilateral hemispheres of the posterior brain, we observed saliency-evoked alpha power increase peaking at the 250ms-centered bin. According to Klimesch's theory (*58*), this early alpha increase ('inhibition') might be engaged by top-down attention to suppress background noise, thus allowing salient signals to pop out. After that, attentional capture and its related conscious perception are more probable during the subsequent period ('dis-inhibition' or 'excitation') with alpha-power decreasing (Fig.**3d**) from peak (centered at 250ms) to trough (centered at 550ms).

Another evidence for such early preparation is the finding that top-down attention had induced global decoupling at the 0-300ms early bin. And, importantly, this global decoupling is accompanied by elevated decoding for both saliency presence and saliency category signals (i.e., Attentional gain; see Fig.**3b** and **4d** for power-based decoding results; see Fig.**5d** and **5f** for coherence-based decoding results). These findings align with previous studies showing that top-down attention enhances early visual processing by decorrelating neuronal firing in the visual system (*77, 78*). Collectively, these findings thus point the possibility that top-down

attention engages alpha band activity to disrupt original coherence patterns at the early stage, so as to allow stimulus-specific salient signals pop out from the background noise.

Separating conscious Vs. post-perceptual activity

Findings here about the global late content retrieval process provides a candidate biomarker to temporally disentangle conscious versus post-perceptual activity. This late retrieval event is strongly evidenced by saliency category signal which displayed a prominent expansion in both amplitude and generalization width at late stages, while simultaneously the saliency presence signals kept declining over time and across the whole brain (see Fig. **4d** and **4g**). On the one hand, these complement prior research reporting similar signal dissociation evidences in visual recognition (*62-64*) and action control (*65*). On the other hand, these signal-dissociation patterns provide a valid marker to identify post-perceptual processes. Given that the long-standing confounding between conscious experience and post-perceptual processing has greatly restricted progress in this field (*1, 34-36, 39*), this newly identified marker enables researchers to separately explore conscious access and post-perceptual response, thereby promoting the advance of consciousness research.

Before late content retrieval, we observed an earlier content Cluster 1 (350-450ms) at the frontal brain. Proponents of GNWT might regard it as a sign of successful 'ignition' through which content signals enter into the global neuronal workspace at the frontal brain, and consciousness would have arisen from the subsequent global broadcasting process through which the frontal neuronal workspace broadcasts content signals back to widely distributed posterior regions. However, we found saliency category signals in posterior cortical regions decreased rather than increased during the time window, which is incompatible with a broadcasting framework, as no more content information was represented in posterior areas. Second, though attentional gain analysis for this cluster revealed a giant increase for saliency presence signals, the same analysis only revealed a weak, non-significant increase for saliency category signals (Fig. **4d**), which is incompatible with giant increase of consciousness switching from unattended to attended state.

We therefore propose an alternative interpretation: saliency category signals within Cluster 1 constitute the neural substrate for rapid, reflexive behavioral responses. This interpretation is supported by behavioral evidence that human reaction times for rapid visual categorization typically peak around 400 ms (*83*), a timeline that closely matches the temporal profile of Cluster 1 activation. Pulling together, it is possible that the frontal Cluster 1 and Cluster 2 support reflexive fast post-perceptual response and deliberate slow post-perceptual response, respectively. Rather, the transient silent interval (roughly 450-600ms) separating the two clusters may reflect an activity-silent mechanism, in which altered synaptic efficacy maintains mnemonic content information in the absence of overt cortical content representations (*32, 33*).

This 'Fast-to-Slow' response account provides plausible interpretation for a recent open-science adversarial collaboration study (*68*) which examined how the frontal brain encodes multidimensional conscious visual features (i.e., category, identity and orientation) and how

these neural content representations track prolonged stimulus duration (up to 2 s). In the frontal brain, they identified frontal encoding for category and identify dimensions but not significant for the orientation dimension. What's more, such truncated frontal encoding emerged exclusively at stimulus onset, with no detectable offset response. These findings could be well reconciled by the 'fast-to-slow' response account discussed above. For the fast response following stimulus onset, it is reasonable to assume that our brain has evolved with a higher priority to encode category and identity dimensions, than to encode the orientation dimension, to support reflexive but biologically adaptive responses immediately after we consciously 'see' some threatening stimuli (e.g., fight or flight). And, at stimulus offset, when only a binary yes/no judgement decision was required at the collaboration study paradigm (*68*), the diminished offset frontal content representations can be reasonably interpreted as a result of eliminated response demand for these early encoded dimensions.

Conscious frontal-posterior coupling

The most salient finding of this study is the binary, category-invariant frontal-posterior coupling that differentiates solely between visible and invisible stimuli, rather than encoding the fine-grained perceptual content of visual inputs. At first glance, this conclusion seems inconsistent with previous fMRI and iEEG studies (*37, 38*), which demonstrated distinct long-range functional coupling patterns corresponding to different perceptual categories (e.g., discriminating houses from faces). Nevertheless, those earlier results were likely confounded by neural activities related to either early preparatory processing or late post-perceptual responses. In line with this view, our iEEG data confirmed category-specific coherence patterns for the Frontal-Posterior group in both the early (Fig.**S14**) and late stages (Fig. **4j**)—despite of absence of frontal-posterior coupling. This indicates that frontal-posterior coupling is not a prerequisite for interregional information transmission; instead, it better serves as a general neural mechanism for salient images to capture attention and thus proportionally promote visual consciousness. If the critical frontal-posterior coupling is disrupted—as in anesthesia, sleep, or coma where frontal-posterior coupling collapses (*84*)—consciousness for external stimuli is abolished, even though residue sensory representations persist in posterior cortical regions (*85*).

Advocates of IIT might nevertheless counter that posterior content representations can translate into explicit conscious experience, provided these posterior regions enter a coupled state. Our data directly undermine this claim. Specifically, posterior coupling was also detected under unattended conditions, and critically, this unattended coupling emerged even earlier than the coupling observed in attended trials (Fig.**S14~16**). If this early posterior coupling evoked by unattended peripheral salient images were sufficient to produce conscious perception, participants would have explicitly experienced two separate foci of visual awareness, one anchored to the central stream and another to the peripheral visual field. However, no participants reported any concurrent peripheral visual experience unless they voluntarily split attention between the two streams, as tested in the partially attended condition of our psychophysical paradigm (Movie.**S2**).

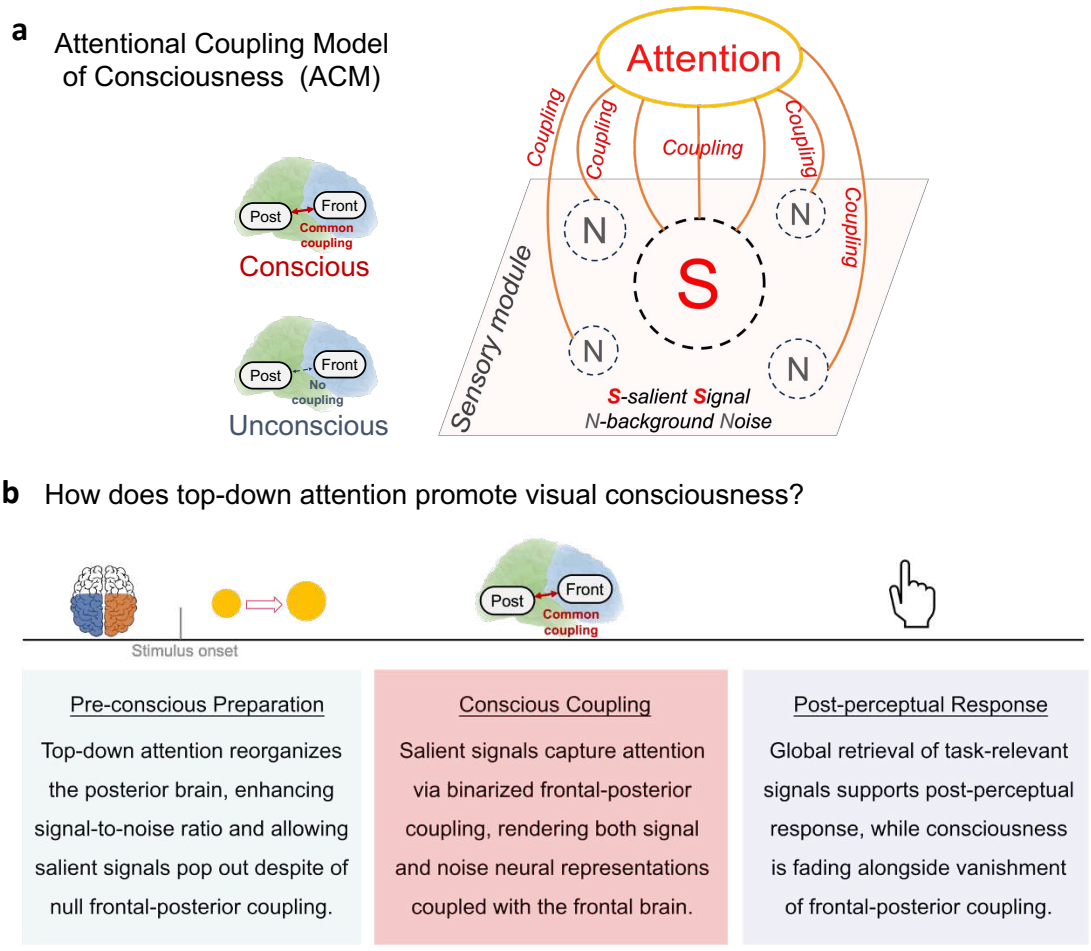


Figure 6. The newly proposed model and brief summary of the present study. a, Graphic illustration of the newly proposed Attentional Coupling Model (ACM) of consciousness. The core idea is that the binary frontal-posterior coupling renders all content representations, including both salient signals and their nested backgrounds, into a binary state of consciousness. **b,** Answers for our initially raised question "How does top-down attention promote visual consciousness".

The discovery of binary nature of frontal-posterior coupling inspires us to propose a new model, the Attentional Coupling Model (ACM, Fig.**6a**) of consciousness. ACM is a cognitive and neurobiological model, though its computational dynamics still need clarification. According to ACM, attention cannot directly enhance conscious perception at the initial early stage though it has greatly boosted saliency presence signal of the stimulus. Rather, ACM proposes that attention enhances conscious perception till to the subsequent intermediate stage, rendering both previously popped-out signals (S) and suppressed noises (N) into conscious state by establishing content-invariant, common frontal-posterior coupling between the frontal module of attention and posterior module of sensory content. In behavior, this global coupling mechanism optimally supports an attentional capture process which as proved in Exp.1 directly contributes to conscious visibility.

After early preconscious preparation, it should be emphasized that the figure-ground segregation problem(*86, 87*) has been solved, allowing the visual system segments images into foreground figures and background noises. Thus, during the subsequent attentional capture process, posterior brain content representations encompass both of them. An intuitive view is that it is only the popped-out foreground salient signals rather than the suppressed noises that would establish functional coupling with the frontal brain. However, the binary nature of frontal-posterior coupling suggests that once this frontal-posterior coupling is initialized, both popped out signals and background noises are integrated into a transient, unified neural synchronization with the frontal brain. As we see it, this binary coupling mechanism provides plausible means to concurrently render all content representations (i.e., signals and noises) into visual consciousness, thus producing a unified experience whereby foreground signals are intrinsically nested within their contextual backgrounds.

Theoretically, ACM avoids IIT's critics of panpsychism (*88, 89*) because it restricts consciousness to functionally-specific biological basis—these neuronal substrates should be capable to functionally direct attention and represent sensory contents respectively, and their binary coupling is required. Compared to other globalist views of consciousness like GNWT, ACM not only provides pioneering evidence showing how this global mechanism operates, but also provides a functional interpretation (i.e., content signals capture attention) for why this global coupling mechanism could generate/promote consciousness. Also, remarkably, ACM holds that the complex content representations locally processed in the posterior brain could get to be consciously perceived via a quite simple mechanism (i.e., binary frontal-posterior coupling), but not necessarily requiring these hybrid representations to be broadcasted across the whole brain. In fact, our findings about the global late content retrieval phenomenon (**Fig.4d, 4g** and **5j**) demonstrate this global broadcasting mechanism supports late post-perceptual response but not perceptual consciousness per se.

Synthesizing all together, we can now address the core question raised at the outset: how does top-down attention promote visual consciousness? In brief (Fig.**6b**), top-down attention initiates early preconscious preparatory processes to allow stimulus-specific salient signals pop out from background noise, even in the absence of frontal-posterior coupling. Salient signals subsequently trigger attentional capture via binary frontal-posterior coupling, and salient signals get consciously perceived via this coupling as being concurrently nested within contextual background noise. In the final stage, global retrieval of task-relevant content representations sustains post-perceptual responses, while conscious experience fades along with the breakdown of frontal-posterior coupling.

Limitation and Conclusion

Several notable limitations of the current study should be acknowledged. To begin with, the sparse intracranial iEEG electrode coverage failed to achieve simultaneous recordings across frontal and occipital cortical hubs, prohibiting direct quantitative connectivity analysis between these two core regions. Second, the inherent correlational nature of iEEG neural analyses

constrains rigorous causal inference regarding how top-down and captured attention directly modulate visual consciousness. Third, subcortical modulators of frontal-posterior coupling remain uncharacterized herein, especially thalamic and pulvinar nuclei. Prior work has validated thalamic gating effects on transient conscious perception(*90*), yet its exact functional role remains elusive: whether the thalamus acts as a non-essential arousal regulator (*91*), a core node for early preconscious preparation analogous, or a direct participant mediating conscious coupling mechanism.

Despite the above limitations, the present study represents a progress in unpacking the relationship between attention and consciousness. Of particular significance, we clarified three distinct neural stages consisting of preconscious preparation, conscious frontal-posterior coupling and post-perceptual response. As artificial intelligence research advances toward the development of conscious intelligent agents (*92, 93*), findings here and the newly proposed ACM model provide biologically plausible insights for optimizing next-generation AI architectures that hopefully link attention, consciousness and action.

References

1. M. A. Pitts, L. A. Lutsyshyna, S. A. Hillyard, The relationship between attention and consciousness: an expanded taxonomy and implications for 'no-report' paradigms. *Philos Trans R Soc Lond B Biol Sci* **373**, (2018).
2. A. K. Seth, T. Bayne, Theories of consciousness. *Nature Reviews Neuroscience* **23**, 439-452 (2022).
3. C. Koch, N. Tsuchiya, Attention and consciousness: two distinct brain processes. *Trends in Cognitive Sciences* **11**, 16-22 (2006).
4. L. Reddy, P. Wilken, C. Koch, Face-gender discrimination is possible in the near-absence of attention. *J Vis* **4**, 106-117 (2004).
5. L. Reddy, L. Reddy, C. Koch, Face identification in the near-absence of focal attention. *Vision Research* **46**, 2336-2343 (2006).
6. F. F. Li, R. VanRullen, C. Koch, P. Perona, Rapid natural scene categorization in the near absence of attention. *Proceedings of the National Academy of Sciences* **99**, 9596-9601 (2002).
7. N. Block, Two neural correlates of consciousness. *Trends in Cognitive Sciences* **9**, 46-52 (2005).
8. A. Pascual-Leone, V. Walsh, Fast backprojections from the motion to the primary visual area necessary for visual awareness. *Science* **292**, 510-512 (2001).
9. J. Silvanto, A. Cowey, N. Lavie, V. Walsh, Striate cortex (V1) activity gates awareness of motion. *Nature Neuroscience* **8**, 143-144 (2005).
10. C. Mazzi, F. Mancini, S. Savazzi, Can IPS reach visual awareness without V1? Evidence from TMS in healthy subjects and hemianopic patients. *Neuropsychologia* **64**, 134-144 (2014).
11. N. Qin, S. Wiens, K. Rauss, G. Pourtois, Effects of selective attention on the C1 ERP component: A systematic review and meta-analysis. *Psychophysiology* **59**, e14123 (2022).
12. S. D. Slotnick, Attentional modulation of early visual areas. *Cogn Neurosci* **9**, 1-3 (2018).

13. R. Eklund, S. Wiens, Visual awareness negativity is an early neural correlate of awareness: A preregistered study with two Gabor sizes. *Cogn Affect Behav Neurosci* **18**, 176-188 (2018).
14. C. Dembski, C. Koch, M. Pitts, Perceptual awareness negativity: a physiological correlate of sensory consciousness. *Trends Cogn Sci* **25**, 660-670 (2021).
15. D. Filimonov, M. Koivisto, A. Revonsuo, New evidence and challenges in ERP and MEG correlates of consciousness in vision: A systematized review. *NeuroImage* **327**, 121762 (2026).
16. C. Sergent, S. Baillet, S. Dehaene, Timing of the brain events underlying access to consciousness during the attentional blink. *Nature Neuroscience* **8**, 1391-1400 (2005).
17. M. Koivisto, A. Revonsuo, An ERP study of change detection, change blindness, and visual awareness. *Psychophysiology* **40**, 423-429 (2003).
18. R. Rutiku, J. Aru, T. Bachmann, General Markers of Conscious Visual Perception and Their Timing. *Frontiers in Human Neuroscience* **Volume 10 - 2016**, (2016).
19. Ł. Doradzińska, M. Bola, Early Electrophysiological Correlates of Perceptual Consciousness Are Affected by Both Exogenous and Endogenous Attention. *Journal of Cognitive Neuroscience* **36**, 1297-1324 (2024).
20. B. Sun, X. Zeng, X. Chen, J. Zhao, S. Fu, Neural correlates of conscious processing of emotional faces: Evidence from event-related potentials. *Neuropsychologia* **182**, 108478 (2023).
21. K. Ciupińska *et al.*, The influence of spatial and temporal attention on visual awareness—a behavioral and ERP study. *Cerebral Cortex* **34**, (2024).
22. G. Tononi, M. Boly, M. Massimini, C. Koch, Integrated information theory: from consciousness to its physical substrate. *Nature Reviews Neuroscience* **17**, 450-461 (2016).
23. V. A. F. Lamme, Towards a true neural stance on consciousness. *Trends in Cognitive Sciences* **10**, 494-501 (2006).
24. B. J. Baars, N. Geld, R. Kozma, Global Workspace Theory (GWT) and Prefrontal Cortex: Recent Developments. *Frontiers in Psychology* **12**, (2021).
25. B. J. Baars, in *Progress in Brain Research,* S. Laureys, Ed. (Elsevier, 2005), vol. 150, pp. 45-53.
26. S. Dehaene, L. Naccache, Towards a cognitive neuroscience of consciousness: basic evidence and a workspace framework. *Cognition* **79**, 1-37 (2001).
27. R. Brown, H. Lau, J. E. LeDoux, Understanding the Higher-Order Approach to Consciousness. *Trends Cogn Sci* **23**, 754-768 (2019).
28. R. Xia, X. Chen, T. A. Engel, T. Moore, Common and distinct neural mechanisms of attention. *Trends in Cognitive Sciences* **28**, 554-567 (2024).
29. Timothy J. Buschman, S. Kastner, From Behavior to Neural Dynamics: An Integrated Theory of Attention. *Neuron* **88**, 127-144 (2015).
30. J. B. Hopfinger, M. H. Buonocore, G. R. Mangun, The neural mechanisms of top-down attentional control. *Nat Neurosci* **3**, 284-291 (2000).
31. T. J. Buschman, E. K. Miller, Top-down versus bottom-up control of attention in the prefrontal and posterior parietal cortices. *Science* **315**, 1860-1862 (2007).

32. M. G. Stokes, 'Activity-silent' working memory in prefrontal cortex: a dynamic coding framework. *Trends Cogn Sci* **19**, 394-405 (2015).
33. D. Trübutschek *et al.*, A theory of working memory without consciousness or sustained activity. *Elife* **6**, (2017).
34. J. M. Fine, B. Y. Hayden, The whole prefrontal cortex is premotor cortex. *Philosophical Transactions of the Royal Society B: Biological Sciences* **377**, 20200524 (2022).
35. P. Haggard, Human volition: towards a neuroscience of will. *Nature Reviews Neuroscience* **9**, 934-946 (2008).
36. S. Frässle, J. Sommer, A. Jansen, M. Naber, W. Einhäuser, Binocular rivalry: frontal activity relates to introspection and action but not to perception. *J Neurosci* **34**, 1738-1747 (2014).
37. R. Hardstone *et al.*, Long-term priors influence visual perception through recruitment of long-range feedback. *Nature Communications* **12**, 6288 (2021).
38. V. A. Weilnhammer, K. Ludwig, G. Hesselmann, P. Sterzer, Frontoparietal cortex mediates perceptual transitions in bistable perception. *J Neurosci* **33**, 16009-16015 (2013).
39. J. Aru, T. Bachmann, W. Singer, L. Melloni, Distilling the neural correlates of consciousness. *Neuroscience & Biobehavioral Reviews* **36**, 737-746 (2012).
40. S. Dehaene, J.-P. Changeux, Experimental and Theoretical Approaches to Conscious Processing. *Neuron* **70**, 200-227 (2011).
41. M. A. Cohen, K. Ortego, A. Kyroudis, M. Pitts, Distinguishing the Neural Correlates of Perceptual Awareness and Postperceptual Processing. *J Neurosci* **40**, 4925-4935 (2020).
42. R. Marois, J. Ivanoff, Capacity limits of information processing in the brain. *Trends in Cognitive Sciences* **9**, 296-305 (2005).
43. J. Duncan, The demonstration of capacity limitation. *Cognitive Psychology* **12**, 75-96 (1980).
44. K. Watanabe, S. Funahashi, Neural mechanisms of dual-task interference and cognitive capacity limitation in the prefrontal cortex. *Nature Neuroscience* **17**, 601-611 (2014).
45. C. Sergent *et al.*, Cueing Attention after the Stimulus Is Gone Can Retrospectively Trigger Conscious Perception. *Current Biology* **23**, 150-155 (2013).
46. B. A. Wandell, J. Winawer, in *Encyclopedia of the Human Brain (Second Edition),* J. H. Grafman, Ed. (Elsevier, Oxford, 2025), pp. 360-381.
47. C. Koch, M. Massimini, M. Boly, G. Tononi, Posterior and anterior cortex — where is the difference that makes the difference? *Nature Reviews Neuroscience* **17**, 666-666 (2016).
48. G. G. Gregoriou, A. F. Rossi, L. G. Ungerleider, R. Desimone, Lesions of prefrontal cortex reduce attentional modulation of neuronal responses and synchrony in V4. *Nature Neuroscience* **17**, 1003-1011 (2014).
49. R. F. Helfrich *et al.*, Neural Mechanisms of Sustained Attention Are Rhythmic. *Neuron* **99**, 854-865.e855 (2018).
50. I. C. Fiebelkorn, M. A. Pinsk, S. Kastner, A Dynamic Interplay within the Frontoparietal Network Underlies Rhythmic Spatial Attention. *Neuron* **99**, 842-853.e848 (2018).
51. V. A. F. Lamme, P. R. Roelfsema, The distinct modes of vision offered by feedforward and recurrent processing. *Trends in Neurosciences* **23**, 571-579 (2000).
52. E. A. DeYoe *et al.*, Mapping striate and extrastriate visual areas in human cerebral cortex. *Proc Natl Acad Sci U S A* **93**, 2382-2386 (1996).

53. Y. Wang *et al.*, Multimodal gradients unify local and global cortical organization. *Nature Communications* **16**, 3911 (2025).
54. A. Ikkai, S. Dandekar, C. E. Curtis, Lateralization in Alpha-Band Oscillations Predicts the Locus and Spatial Distribution of Attention. *PLOS ONE* **11**, e0154796 (2016).
55. M. Bonnefond, O. Jensen, The role of alpha oscillations in resisting distraction. *Trends in Cognitive Sciences* **29**, 368-379 (2025).
56. M. Suzuki, J. Gottlieb, Distinct neural mechanisms of distractor suppression in the frontal and parietal lobe. *Nat Neurosci* **16**, 98-104 (2013).
57. O. Jensen, Distractor inhibition by alpha oscillations is controlled by an indirect mechanism governed by goal-relevant information. *Communications Psychology* **2**, 36 (2024).
58. W. Klimesch, Alpha-band oscillations, attention, and controlled access to stored information. *Trends in Cognitive Sciences* **16**, 606-617 (2012).
59. F. Duecker, A. T. Sack, The hybrid model of attentional control: New insights into hemispheric asymmetries inferred from TMS research. *Neuropsychologia* **74**, 21-29 (2015).
60. M. Kinsbourne, Hemi-neglect and hemisphere rivalry. *Adv Neurol* **18**, 41-49 (1977).
61. M. A. Pitts, J. Padwal, D. Fennelly, A. Martínez, S. A. Hillyard, Gamma band activity and the P3 reflect post-perceptual processes, not visual awareness. *NeuroImage* **101**, 337-350 (2014).
62. M. Mishkin, L. G. Ungerleider, K. A. Macko, Object vision and spatial vision: two cortical pathways. *Trends in Neurosciences* **6**, 414-417 (1983).
63. J. M. Hillis, D. H. Brainard, Distinct Mechanisms Mediate Visual Detection and Identification. *Current Biology* **17**, 1714-1719 (2007).
64. L. Li, X. Shen, S. Kuai, Distinct detection and discrimination sensitivities in visual processing of real versus unreal optic flow. *Psychonomic Bulletin & Review*, (2025).
65. L.-M. Schöpper, M. D. Hilchey, M. Lappe, C. Frings, Detection versus discrimination: The limits of binding accounts in action control. *Attention, Perception, & Psychophysics* **82**, 2085-2097 (2020).
66. Z. Fang *et al.*, Human high-order thalamic nuclei gate conscious perception through the thalamofrontal loop. *Science* **388**, eadr3675 (2025).
67. B. van Vugt *et al.*, The threshold for conscious report: Signal loss and response bias in visual and frontal cortex. *Science* **360**, 537-542 (2018).
68. O. Ferrante *et al.*, Adversarial testing of global neuronal workspace and integrated information theories of consciousness. *Nature* **642**, 133-142 (2025).
69. A. Clark, Whatever next? Predictive brains, situated agents, and the future of cognitive science. *Behav Brain Sci* **36**, 181-204 (2013).
70. G. Buzsáki, M. Vöröslakos, Brain rhythms have come of age. *Neuron* **111**, 922-926 (2023).
71. J. W. Y. Kam *et al.*, Default network and frontoparietal control network theta connectivity supports internal attention. *Nature Human Behaviour* **3**, 1263-1270 (2019).
72. N. Gaspelin, S. J. Luck, The Role of Inhibition in Avoiding Distraction by Salient Stimuli. *Trends in Cognitive Sciences* **22**, 79-92 (2018).
73. X. Wu, X. Zhang, Y. Jiang, L. Wang, Modulation Effect and Potential Mechanisms of Selective Attention on Unconscious Processing. *Progress in Biochemistry and Biophysics* **51**, 2016-2027 (2024).

74. X. Wu, X. Zhang, L. Wang, Y. Jiang, Unconscious Fear Requires Attention to Distort Vision in Safe Context. *Neuroscience Bulletin*, (2026).
75. B. T. Stilwell, O. J. Adams, H. E. Egeth, N. Gaspelin, The role of salience in the suppression of distracting stimuli. *Psychonomic Bulletin & Review*, (2023).
76. R. Sawaki, S. J. Luck, Capture versus suppression of attention by salient singletons: electrophysiological evidence for an automatic attend-to-me signal. *Atten Percept Psychophys* **72**, 1455-1470 (2010).
77. M. R. Cohen, J. H. R. Maunsell, Attention improves performance primarily by reducing interneuronal correlations. *Nature Neuroscience* **12**, 1594-1600 (2009).
78. J. F. Mitchell, K. A. Sundberg, J. H. Reynolds, Spatial Attention Decorrelates Intrinsic Activity Fluctuations in Macaque Area V4. *Neuron* **63**, 879-888 (2009).
79. Conrado A. Bosman *et al.*, Attentional Stimulus Selection through Selective Synchronization between Monkey Visual Areas. *Neuron* **75**, 875-888 (2012).
80. L. I. Schmitt *et al.*, Thalamic amplification of cortical connectivity sustains attentional control. *Nature* **545**, 219-223 (2017).
81. Y. B. Saalmann, M. A. Pinsk, L. Wang, X. Li, S. Kastner, The pulvinar regulates information transmission between cortical areas based on attention demands. *Science* **337**, 753-756 (2012).
82. H. Zhou, R. J. Schafer, R. Desimone, Pulvinar-Cortex Interactions in Vision and Attention. *Neuron* **89**, 209-220 (2016).
83. M. Fabre-Thorpe, The Characteristics and Limits of Rapid Visual Categorization. *Frontiers in Psychology* **2**, (2011).
84. R. Zelmann *et al.*, Differential cortical network engagement during states of un/consciousness in humans. *Neuron* **111**, 3479-3495 e3476 (2023).
85. A. J. Krom *et al.*, Anesthesia-induced loss of consciousness disrupts auditory responses beyond primary cortex. *Proceedings of the National Academy of Sciences* **117**, 11770-11780 (2020).
86. P. R. Roelfsema, V. A. F. Lamme, H. Spekreijse, H. Bosch, Figure—Ground Segregation in a Recurrent Network Architecture. *Journal of Cognitive Neuroscience* **14**, 525-537 (2002).
87. V. A. Lamme, The neurophysiology of figure-ground segregation in primary visual cortex. *J Neurosci* **15**, 1605-1615 (1995).
88. S. Fleming *et al.*, The Integrated Information Theory of Consciousness as Pseudoscience. (2023).
89. S. B. Yurchenko, Panpsychism and dualism in the science of consciousness. *Neuroscience & Biobehavioral Reviews* **165**, 105845 (2024).
90. Z. Fang *et al.*, Intracranial neural representation of phenomenal and access consciousness in the human brain. *NeuroImage* **297**, 120699 (2024).
91. Y. Wang *et al.*, A common thalamic hub for general and defensive arousal control. *Neuron* **111**, 3270-3287.e3278 (2023).
92. P. Butlin *et al.*, Consciousness in Artificial Intelligence: Insights from the Science of Consciousness. *ArXiv* **abs/2308.08708**, (2023).

93. L. Blum, M. Blum, A theory of consciousness from a theoretical computer science perspective: Insights from the Conscious Turing Machine. *Proceedings of the National Academy of Sciences* **119**, e2115934119 (2022).

Acknowledgements

We give thanks to Xiangyong Yuan and Chencan Qian for insightful comments on earlier version manuscript, to Zhihao Guo and Bingqing Zhang for help in iEEG data collection, and to Haiyan Kong and Chenyu Gao for help in behavior data collection.

Funding:

This work was supported by grants from STI2030-Major Projects by the Ministry of Science and Technology of China 2021ZD0204200 (SH), 2021ZD0203800 (YJ), 2022ZD0205000 (LW), The National Natural Science Foundation of China 32100863 (XZ), 32020103009 (LW), 31830037 (YJ), 32471110 (LW), and the Scientific Foundation of the Institute of Psychology, Chinese Academy of Sciences E1CX1910 (XZ).

Author contributions:

Conceptualization: XZ, LW, YJ

Methodology: XZ, LW, YJ, KZ

Investigation: XZ, CZ, WZ

Visualization: XZ, LW, YL, ZJ

Funding acquisition: SH, YJ, LW, XZ

Project administration: LW, KZ, XZ

Resources: LW, YJ, KZ

Supervision: LW, KZ, YJ, XZ

Theoretical modelling: XZ

Writing – original draft: XZ

Writing – review & editing: XZ, LW, SH, YJ

Competing interests: Authors declare that they have no competing interests.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- adt3195SupplementaryMoviemov4seq4v1.mp4
- adt3195SupplementaryMoviemov3seq3v1.mp4
- adt3195SupplementaryMoviemov1seq1v1.mp4
- adt3195SupplementaryMoviemov5seq5v1.mp4
- adt3195SupplementaryMoviemov2seq2v1.mp4
- NCManuscriptSupple261026.pdf