Retrospective Attention Can Trigger Visual Perception Without Dependence on Either Cue Awareness or Target Reporting

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SUMMARY

Retrospective attention, directed by cues after stimulus offset, enhances the perception of threshold-level Gabor patches. However, the neural mechanisms and the dependence on cue awareness and target reporting remain unclear. Using EEG in both report and no-report paradigms with visible and invisible post-cues, we found that orientation discrimination improved with retro-cues regardless of cue visibility. Under invisible conditions, retro-cueing effects were weaker, limited to a stimulus onset asynchrony (SOA) of 66.67 ms, and associated with the N2pc component. In contrast, visible retro-cueing persisted at a 100 ms SOA, eliciting strong P3b and weak VAN in report condition. Multivariate pattern analysis revealed that in report conditions, neural processing of cued targets was earlier, stronger, and more generalized in fronto-parietal regions, whereas in no-report conditions, decoding was confined to parieto-occipital areas. These findings indicate that retrospective attention can enhance visual perception independently of cue awareness and target reporting, contributing to ongoing theories of consciousness.

INTRODUCTION

Visual perception is a complex process influenced by various factors, including attention. An intriguing question in visual perception and consciousness research is whether cues presented after the offset of a visual stimulus can induce visual reactivation and retrospectively influence our conscious perception of the stimulus[1,2]. This phenomenon, known as the "retrospective attention effect," has significant implications for our understanding of consciousness and attention.

Recent experiments have confirmed the existence of the retrospective attention effect[3-5]. These studies have demonstrated that retro-cueing attention can retrospectively recover sensory traces that are about to disappear from consciousness, suggesting that retrospective attention acts as a gatekeeper mediating conscious perception [5]. Furthermore, a study by Thibault et al.[4], showed that directing exogenous attention to the target location after its presentation significantly improved

participants' ability to discriminate its orientation, ruling out the hypothesis that the retrospective attention effect stems from working memory rather than a perceptual effect.

However, the interpretation of these findings remains controversial. Some researchers argue that the retro-cueing effect is confounded by various cognitive processes, such as target attention, decision-making and motor functions[6,7,18,25-30]. They contend that results at the behavioral level alone cannot adequately distinguish these processes. Adding to this complexity, a recent study by Stein[7] reported that a local visual interaction between the target and cue is sufficient to trigger consciousness of the target, revealing a new type of retrospective attention effect mediated by sensory (non-attentional) mechanisms. This suggests that exogenous attention may not be the only mechanism contributing to the retrospective attention effect.

While robust effects of post-cue attention have been found in behavioral experiments[4,7,8], the neural mechanisms underlying these effects remain largely unknown. This gap in our understanding is particularly significant given the intricate connections between attention and consciousness identified in previous studies[9,10]. Theories of consciousness, such as the Recurrent Processing Theory (RPT) and the Global Neuronal Workspace Theory (GNWT)[9,10], provide frameworks for understanding these connections but have not been specifically applied to the retro-perception effect.

To address these open questions and distinguish between different types of retro-perception effects, we designed three new experiments incorporating two key paradigms:

The Backward Masking Paradigm[14,15]: This paradigm can generate subliminal cues, thereby blocking top-down information transmission pathways and allowing us to isolate the effects of local visual interactions.

The No-Report Paradigm[11-13]: In this paradigm, participants do not make judgments about their perceptual experience, minimizing the neural correlates of post-perceptual processing[11].

Additionally, we incorporated EEG recordings and multivariate pattern analysis to investigate the neural correlates associated with retro-perception effects. Specifically, we focused on ERP components such as N2pc and P3b[14] to investigate the relationship between consciousness and attention.

By combining these paradigms, we aim to achieve two primary objectives: Dissociate the Two Types of Retro-Perception Effects: One based on local visual sensory interaction mechanisms and the other on attention mechanisms. Distinguish Conscious Perception from Motor Activity: Ensuring that the observed retrospective attention effect indeed enhances participants' conscious perception of the target at the neural level.

We hypothesize that: The Backward Masking Paradigm Will Not Disrupt Sensory-Mediated Retro-Perception Effects[15]. Post-Cue Attention Will Enhance Neural Markers of Conscious Perception, even in the absence of explicit reporting, demonstrating its robustness beyond task-related cognitive processes.

This study contributes to the field by providing the first neural evidence for the mechanisms underlying the retrospective attention effect, potentially reconciling conflicting accounts in the literature. Our findings will have implications for theories of consciousness and attention, offering new insights into the temporal dynamics of conscious perception and the role of post-perceptual processing in awareness. Moreover, by demonstrating the persistence of the post-cue effect in a no-report paradigm, we aim to establish its fundamental role in shaping conscious perception, independent of explicit report.

RESULTS

Experiment 1

We assessed whether post-cue attention[5] could influence the perception of a single stimulus at threshold in an unconscious exogenous attention paradigm[16]. In this paradigm, the attentional cue provided no information on stimulus location, minimizing its influence on decision-making or other post-perceptual processes. The target stimulus was a single low-contrast Gabor patch of random orientation, which could be flashed randomly within one of two circles to the left or right of central fixation (Figure 1A). Participants were required to report the target's orientation. Target contrast was individually calibrated to reach 75% accuracy without cueing.

During the experiment, attention was randomly cued to the left or right by a brief dimming of one circle. Importantly, the dimming prevented masking of the target, unlike more conventional attentional cues such as thickening or abrupt onset of a shape near the target's location. This cue appeared either before (pre-cue) or after (post-cue) the target. Following the cue or target, an 83.33 ms mask or fixation period was presented for the invisible and visible conditions, respectively. At the end of each trial, a response cue (thickening of one side of the fixation cross) indicated the target's side, eliminating location uncertainty. Subsequently, a second response screen appeared, displaying a dimming cross at the fixation point where participants reported the position of the cue in a two-alternative forced choice (2AFC) task. Twenty-four volunteers participated in this experiment.

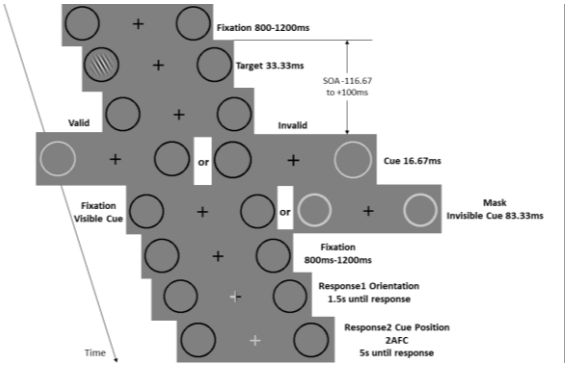
When no mask stimulus was presented (visible cue condition), whether the cue appeared before or after the target, our results replicated the typical time course of pre-cue and post-cue exogenous attention (Figure 2): congruent cues—same side as the target—improved orientation accuracy relative to incongruent cues—opposite side [ANOVA with factors congruency (2) × stimulus onset asynchrony (SOA) (3); congruency: $F(1,23) = 111.64$, $p < 0.001$]. Critically, congruent cues presented after the target also substantially improved orientation discrimination (Figure 2). Post-hoc comparisons with BONFERRONI correction indicated significant differences between valid and invalid cues in all three SOA conditions (-116.67 ms, corrected $p < 0.001$; +66.67 ms, corrected $p < 0.001$; +100 ms, corrected $p < 0.001$). This strong effect persisted 100 ms after the target, mainly due to the benefit of congruent cueing, which improved performance compared to 75% accuracy in the absence of cueing.

When a mask stimulus was presented, although the pre-cue and post-cue exogenous attention effects weakened, congruent cues still improved orientation accuracy relative to incongruent cues [ANOVA with factors congruency (2) × stimulus onset asynchrony (SOA) (3); congruency: $F(1,23) = 16.33$, $p = 0.001$]. Post-hoc comparisons with BONFERRONI correction indicated significant differences between valid and invalid cues in two SOA conditions (-116.67 ms, corrected $p = 0.022$; +66.67 ms, corrected $p = 0.015$), but not in the +100 ms condition (corrected $p = 0.257$) (Figure 2).

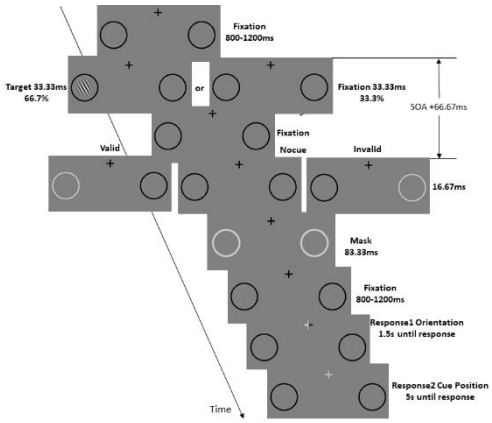
In conclusion, these results show that when a single stimulus is presented, directing attention to its location after its offset can still have a substantial effect on our ability to report a simple feature of this stimulus, such as orientation, even when the cue location is invisible. This indicates that post-cue attention likely reflects a local sensory interaction between the cue and target, rather than post-perceptual processes. Interestingly, we found that the post-cue attention effect vanished when the SOA between the target and the cue reached +100ms in the invisible cue condition. This suggests that the post-cue attention effect is highly time-sensitive under

conditions where the cue location is invisible.

A Experiment 1



B Experiment 2



C Experiment 3

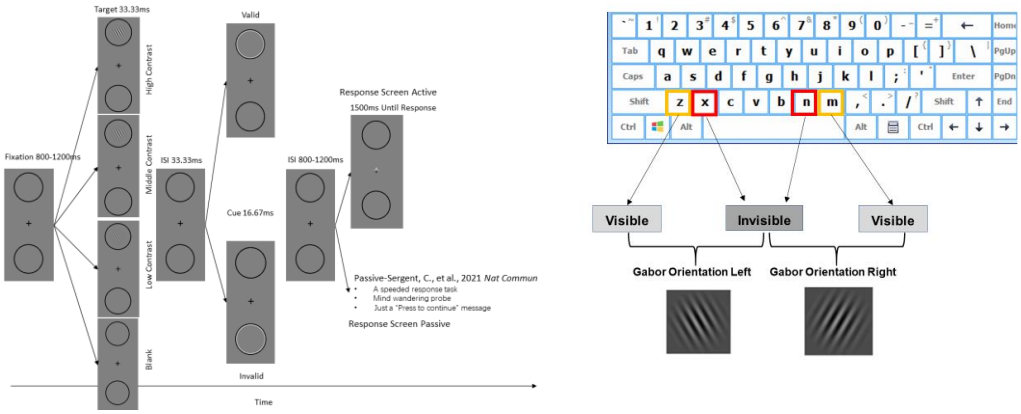


Figure 1. Stimuli and procedures in experiments 1,2,3

(A) Stimulus and Procedure for the Experiments 1: Each trial commenced with the appearance of a fixation cross at the center. After a random delay of 800 to 1200 ms, a target—specifically, a Gabor patch with a random orientation (30° or 150° away from the vertical)—was displayed for 33.33 ms within one of the circles located to the left or right of the

fixation point. The target contrast was individually calibrated for each subject using a staircase method. A 16.67 ms cue, which consisted of a brief dimming of one of the circles, could appear either before or after the target. This cue could be either valid (on the same side as the target) or invalid (on the opposite side). Following the cue, there was an 83.33 ms mask or fixation period for the visible and invisible conditions, respectively. A response screen was presented 800 to 1200 ms after the offset of the mask or fixation, with a response cue indicating the target's side (marked by a thickening and dimming on one side of the cross). Participants were then asked to report the target's orientation by choosing between two options (Left/Right). Subsequently, a second response screen appeared, displaying a dimming cross at the fixation point, where participants reported the position of the cue in a two-alternative forced choice (2AFC) task.

(B) Stimulus and Procedure for the Experiments 2: The stimulus presentation procedure in Experiments 2 is fundamentally similar to that of Experiments 1, with the following modifications: the two circles are placed below the fixation point; the target presentation screen includes a fixation screen with a 1/3 probability (catch trials); the stimulus onset asynchrony (SOA) between the target and the cue is fixed at 66.67 ms; a Non-Cue condition is added to the cue presentation; and only the mask stimulus is presented, thereby maintaining only the invisible condition.

(C) Stimuli and Procedure for Experiments 3: In this experiment, two circles are positioned respectively above and below the fixation point. The Gabor patch and the cue randomly appear in one of the two circles. The physical stimulus intensity is determined for each participant based on the Gabor contrast levels obtained from the staircase test: high contrast - orientation discrimination accuracy near 100%, medium contrast - orientation discrimination accuracy around 75%, and low contrast - orientation discrimination accuracy about 50%. The fixation screen from Experiments 2 is retained for catch trials. On the response screen, the active reporting condition remained consistent with the Gabor patch orientation discrimination task from the previous experiment, with the addition that participants were required to report both the Gabor patch orientation and their subjective visibility. Additionally, a passive viewing condition is introduced, wherein participants are required to complete one of three randomly presented tasks: 1. Speed response task; 2. Mind-wandering detection task; 3. A simple message prompting "Press SPACE to continue"(see Methods for details). On the response screen of Experiments 3, the active reporting condition remained similar to the Gabor patch orientation discrimination task from the previous experiment. However, participants were now required to identify both the orientation of the Gabor patch (Left or Right) and rate its subjective visibility ("visible" or "invisible") simultaneously. This modification resulted in four response options for each trial.

Behavioral results in experiment 1

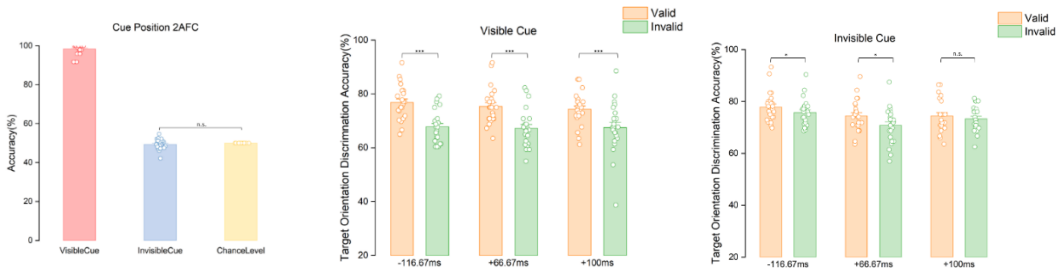


Figure 2. Experiment1 Behavioral results.

Left: Cue Position Discrimination 2AFC Task in Experiment 1: Dots represent individual performance. Accuracy is presented on the y-axis, and the different visible cues are presented on the x-axis. Error bars represent the standard error of the mean.

Middle, right: Target Orientation Discrimination 2AFC Task in Experiment 1: Dots represent individual performance, with chance level at 50%. Accuracy is presented on the y-axis. The different target-cue SOA conditions are presented on the x-axis. Under the visible cue condition, all three selected target-cue SOA conditions exhibited the classic pre-cue and post-

cue effects, with accuracy in the valid cue condition significantly higher than in the invalid cue condition. Middle shows the visible cue condition, while right shows the invisible cue condition.

Experiment 2

Behavior Results

This second experiment, including 23 new volunteers, was similar to the previous one except that the SOA between the target and the cue was fixed at 66.67 ms; a Nocue condition was added to the cue presentation; and only the mask stimulus was presented, thereby maintaining only the invisible condition (Figure 3). Results on the objective orientation discrimination task replicated the results of the first experiment (Figure 3) [congruency: $F(1,20) = 5.66$, $p = 0.011$]. Post-hoc comparisons with BONFERRONI correction indicated significant differences between valid and invalid cues (corrected $p = 0.002$), but not between valid and nocue condition (corrected $p = 0.169$).

EEG Results

The N2pc in the report and no-report conditions in experiment 2

Results from the N2pc analysis are shown in Figure 4. N2pc amplitudes significantly differed between the contralateral and ipsilateral electrodes across the three congruency conditions [ANOVA with factors congruency (valid/invalid/nocue, 3) × electrodes (ipsilateral/contralateral, 2): $F(2, 20) = 2.264$, $p = 0.129$; electrodes: $F(1, 22) = 30.39$, $p < 0.001$]. Post-hoc comparisons with BONFERRONI correction indicated significant differences between contralateral and ipsilateral electrodes in all three congruency conditions (Figure 4A, valid, corrected $p < 0.001$; Figure 4A, invalid, corrected $p = 0.006$; Figure 4B, nocue, corrected $p < 0.001$). N2pc difference wave amplitudes (contralateral minus ipsilateral) significantly differed between the valid, nocue and invalid conditions [ANOVA with factors congruency (valid/invalid/nocue, 3): $F(2, 20) = 14.76$, $p < 0.001$]. Post-hoc comparisons with BONFERRONI correction indicated significant differences not only between valid and invalid conditions but not between valid and nocue conditions (valid versus invalid, corrected $p = 0.025$; valid versus nocue, corrected $p = 0.231$; invalid versus nocue, corrected $p = 0.029$). The results showed that even under conditions where the cue was invisible, post-cue attention could still modulate the classic attention-related ERP component-N2pc.

Behavioral results in experiment 2

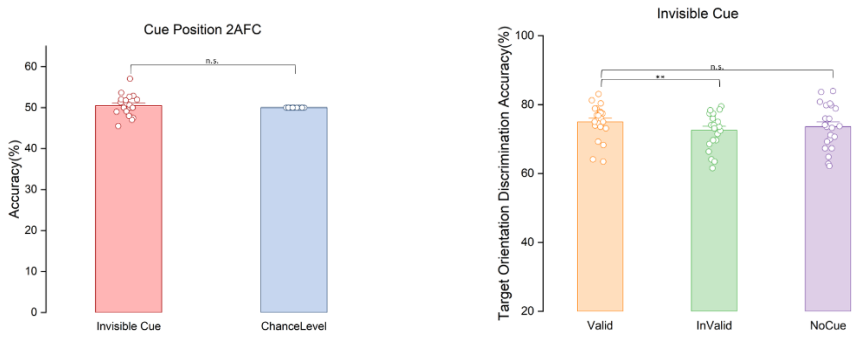


Figure 3. Experiment 2 Behavioral results.

Left: Cue Position Discrimination 2AFC Task in Experiment 2, dots represent individual performance. Accuracy is presented on the y-axis, and the different visible cues are presented on the x-axis. Error bars represent the standard error of the

mean.

Right: Target Orientation Discrimination 2AFC Task in Experiment 2, dots represent individual performance, with chance level at 50%. Accuracy is presented on the y-axis. The different cue attention conditions (Valid, Invalid, and No-cue) are presented on the x-axis.

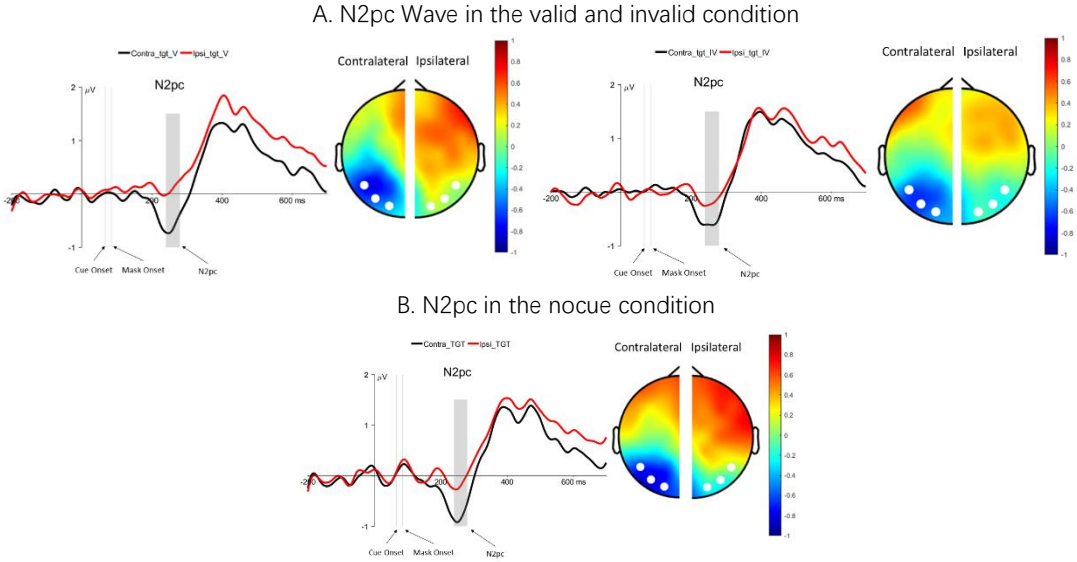


Figure 4. Visualizations of the N2pc in experiment2

A-valid, invalid, B-noncue, left: N2pc waveforms for contralateral and ipsilateral sides plotted over time. Shaded areas represent the time window for mean amplitude used for statistical testing (240-280 ms). Right: Topographical voltage distributions between 240-280 ms with all electrodes used to analyze the N2pc indicated on the scalp map.

Experiment 3

Behavior results

This third experiment, involving 20 new participants, was similar to the first experiment but with several key modifications. The stimulus onset asynchrony (SOA) between the target and the cue was fixed at 66.67 ms. Only the fixation stimulus was presented, maintaining the visible condition. Two circles were positioned above and below the fixation point, with the Gabor patch and the cue randomly appearing in one of these circles (Figure 1C).

A significant addition was the introduction of three Gabor contrast levels for the target presentation. These contrast levels followed a linear growth pattern (Figure 6A), with average values of 0.00662 (Low), 0.01845 (Medium), and 0.03088 (High), and standard deviations of 0.00367 (Low), 0.00598 (Medium), and 0.00873 (High).

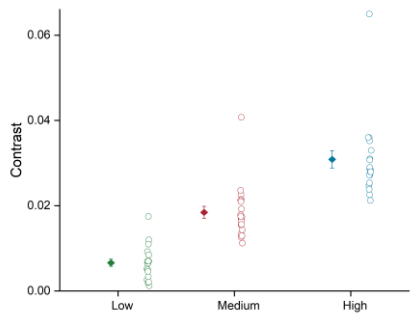
In the report task, accuracy on the objective orientation discrimination task replicated the results of the first experiment (Figure 6B) [congruency: $t(1, 19) = 84.67$, $p < 0.001$]. Post-hoc comparisons with BONFERRONI correction indicated significant differences between valid and invalid cues at the medium Gabor contrast level (corrected $p = 0.002$), but not in the low (corrected $p = 0.776$) and high contrast conditions (corrected $p = 0.079$).

Interestingly, the results for subjective clarity were slightly different, showing a significant post-cue effect across low, medium, and high contrast levels. Post-hoc comparisons with BONFERRONI correction indicated significant differences between valid and invalid cues across low, medium,

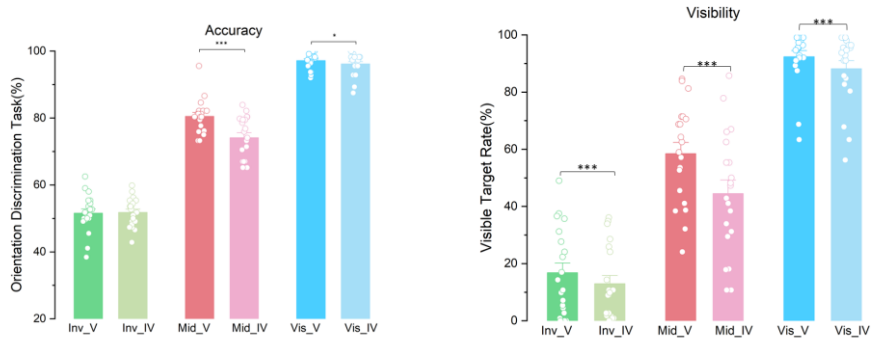
and high contrast levels (low-50% accuracy: corrected p = 0.002; medium-75% accuracy: p < 0.001; high-100% accuracy: p = 0.021). This discrepancy is possibly due to floor and ceiling effects.

In the mind-wandering tasks, almost all subjects reported that they were focusing on the Gabor patch in over 70% of the trials, as well as on the dimming of the circle or the fixation cross (Figure 6C, Average = 0.9589, SD = 0.07918). In the speeded-response task, almost all subjects responded accurately and quickly (in less than 1 second) to press the button (Figure 6C, Average = 0.9920, SD = 0.00862).

A. Different contrasts of the three condition



B. Behavior results in the report condition



C. Behavior results in the no-report condition

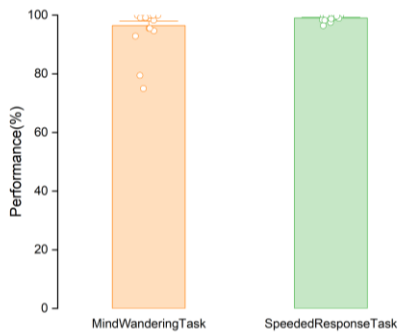


Figure 6. Behavior results in the no-report and report conditions in experiment3

(A) Average contrast levels across three conditions. The x-axis displays the different Gabor patch contrasts (Low, Medium, and High), while the y-axis represents the contrast values. Dots on the right indicate individual contrast levels used to control orientation discrimination performance at 50%, 75%, and 100% accuracy. The graph illustrates the linear progression of contrast levels across the three conditions.

(B) Left: Target Subjective Visibility in Experiment 3: Dots represent individual performance. The proportion of trials in which the target was visible is presented on the y-axis. The different Gabor patch contrasts (Invisible, Medium, and Visible) are presented on the x-axis.

Right: Target Orientation Discrimination 2AFC Task in Experiment 3: Dots represent individual performance, with chance level at 50%. Accuracy is presented on the y-axis. The different target contrast conditions are presented on the x-axis.

(C) Performance on the Mind-Wandering Task and Speeded Response Task in the No-Report Condition. All error bars represent the standard error.

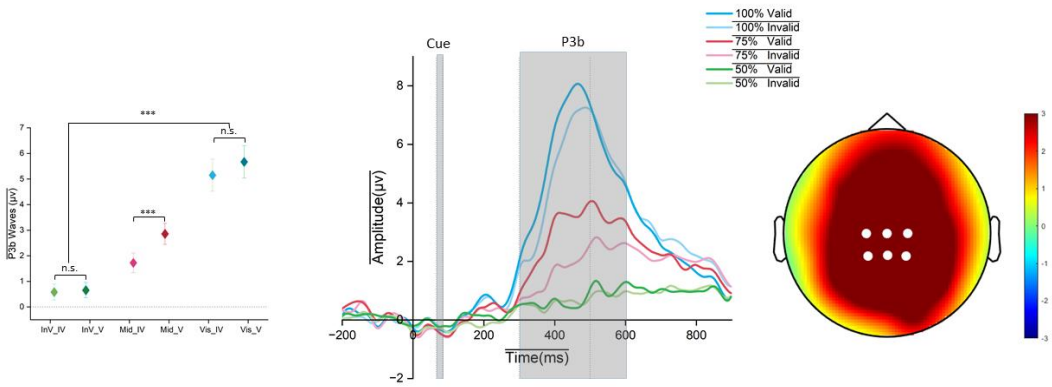
EEG Results

The P3b in the report and no-report conditions in experiment3

The results from the P3b analysis (see Methods) are shown in Figure 7. In the report condition, we observed a post-cueing effect in both high (100%) and medium (75%) contrast conditions for the P3b (medium: valid vs. invalid, $t(19) = 20.131$; $P = 0.001$ and high: valid vs. invalid, $t(19) = 4.77$; $P = 0.046$; Figure 7A), indicating that post-cueing attention can enhance visual perception. There was no difference in P3b amplitude for the two lowest contrast conditions (valid vs. invalid, $t(19) = 0.252$; $P = 0.623$), consistent with previous behavioral studies.

Most importantly, consistent with previous studies[11,13], we found no significant difference in P3b amplitude in the no-report condition (high: valid vs. invalid, $t(19) = 2.516$; $P = 0.129$; medium: valid vs. invalid, $t(19) = 0.344$; $P = 0.565$; low: valid vs. invalid, $t(19) = 0.001$; $P = 0.882$; Figure 7B). Interestingly, in the report task, when plotting the average amplitudes from all electrodes used for the P3b across all six conditions (low-invalid, low-valid, medium-invalid, medium-valid, high-invalid, high-valid), we observed a non-linear, bifurcated-like increase in amplitudes[12,13,17]. This pattern is considered a potential correlate of conscious processing, replicating prior work[17]. However, while we ensured that the three contrast levels were controlled in a linear manner, we could not guarantee that the different attention modulations (valid, invalid) formed a linear pattern. As a result, we did not conduct further in-depth analysis on this particular aspect.

A. P3b in the report condition



B. P3b in the no-report condition

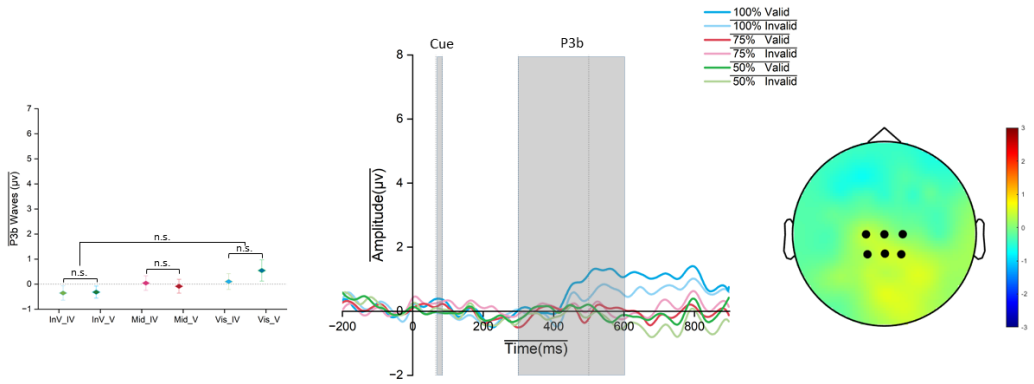


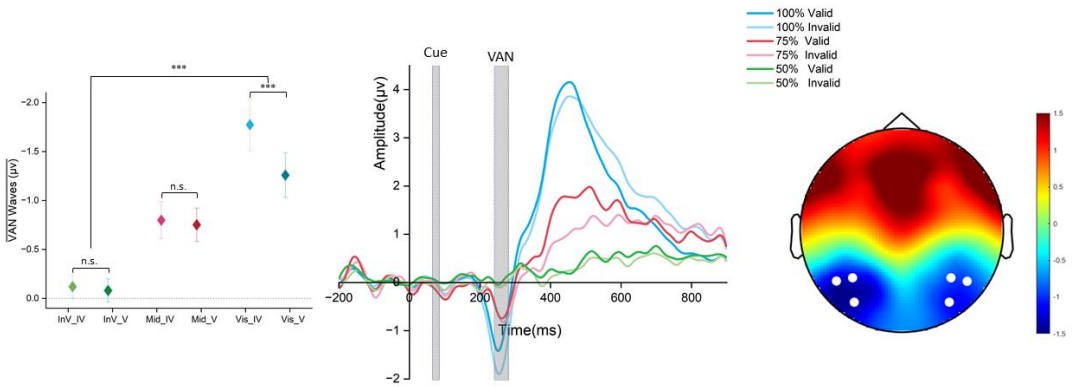
Figure 7. Visualizations of the P3b in the report and no-report conditions in experiment3

(A) Report condition and **(B)** no-report condition. On the left: The average amplitudes from all electrodes used for the P3b across all six conditions. On the center: P3b waveforms for all six conditions (3 contrasts × 2 congruencies) plotted over time. On the right: Topographical voltage distributions between 300-600ms with all electrodes used to analyze the P3b indicated on the scalp map.

The VAN in the report and no-report conditions in experiment3

The "visual awareness negativity" (VAN)[18,19] is defined as a relatively more negative ERP signal for seen compared to unseen stimuli, with a bilateral posterior distribution, roughly in the time window between 150-300 ms. Results from the VAN analysis are shown in Figure 8. In the report condition, we observed a post-cueing effect in the VAN only at high (100%) contrast (high: valid vs. invalid, $t(19) = 9.149$; $P = 0.009$; medium: valid vs. invalid, $t(19) = 0.066$; $P = 0.801$; low: valid vs. invalid, $t(19) = 0.516$; $P = 0.484$; Figure 8A). Interestingly, the VAN pattern is exactly the opposite of the P3b, meaning the VAN amplitude in the invalid condition is more negative than in the valid condition. Similar with the P3b pattern, we found no difference in the VAN between valid and invalid in the no-report condition. (high: invalid vs. valid, $t(19) = 1.251$; $P = 0.277$; medium: invalid vs. valid, $t(19) = 0.023$; $P = 0.882$; low: invalid vs. valid, $t(19) = 0.001$; $P = 0.981$; Figure 8B).

A. VAN in the report condition



B. VAN in the no-report condition

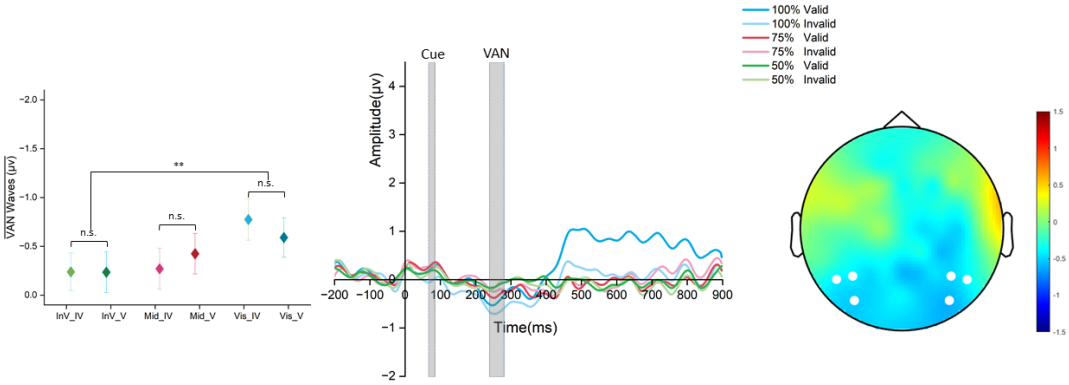


Figure 8. Visualizations of the VAN in the report and no-report conditions in experiment3

(A) Report and **(B)** no-report conditions. On the left: The average amplitudes from all electrodes used for the VAN across all six conditions. On the center: VAN waveforms for all six conditions (3 contrasts × 2 congruencies) plotted over time. On the right: Topographical voltage distributions between 240-280 ms with all electrodes used to analyze the P3b indicated on the scalp map.

Multivariate Analysis Results

We trained linear classifiers for all 62 electrodes to distinguish between target and no-target conditions, using the amplitude across electrodes as features. Classifier performance was evaluated using the area under the curve (AUC) of the receiver operating characteristic (ROC) curve.

Decoding Time Courses in the report condition and no-report condition in experiment3

However, the temporal profiles of decoding performance varied across different contrast and congruency conditions (Figures 9A, 9B). In the report task, significant clusters emerged earlier after stimulus onset in the valid condition compared to the invalid condition for all three contrast conditions (all $p_{cluster} < 0.05$, shown by different color horizontal bars in Figure 9A top). The temporal profiles of difference AUC (valid-invalid) revealed that significant clusters emerged around 400ms after stimulus onset and ended around 500ms in both high and medium contrast conditions (Figure 9A bottom).

In the no-report task, significant clusters emerged only 300ms after stimulus onset in the high contrast-valid condition, but not in the other five conditions (all $p_{cluster} < 0.05$, shown by different color horizontal bars in Figure 9B top). The temporal profiles of difference AUC (valid-invalid) showed that significant clusters emerged around 400ms and ended around 700ms after stimulus onset in only high contrast conditions (Figure 9B bottom).

Searchlight Decoding Analysis in valid and invalid condition in the Report condition and No-report condition in experiment3

To identify the regions with the highest decoding performance in valid and invalid conditions

across three Gabor contrasts, we conducted a Searchlight Decoding Analysis[20-22]. In the report task, the highest performance cluster was clearly localized to the fronto-parietal region electrodes in both medium and high contrast conditions (Supplement Figure 1). However, in the no-report task, the highest performance cluster emerged in a region much closer to the occipital area, specifically in the high contrast condition (Supplement Figure 1).

Temporal Generalization Analysis in the Report condition and No-report condition in experiment3

These findings demonstrate that the retro-cue effect can improve EEG decoding performance for the target Gabor patch and advance its decoding time, regardless of report or no-report task conditions. To test the temporal generalization performance of the retro-cue effect, we applied the temporal generalization method. In this approach, classifiers are trained on data from each time point separately but tested on all time points, resulting in a temporal generalization matrix (TGM; target present vs. target absent: Supplement Figure). Successful decoding between time points (off-diagonal decoding) indicates that the direction in state space discriminating between target and no-target conditions remains stable over time.

The Temporal Generalization Analysis results revealed a pattern similar to the Decoding Time Courses. In the report task, we found strong evidence of a metastable representation associated with conscious perception, indicated by late square-shaped patterns in the temporal generalization matrix (Supplement Figure) in all conditions except the lowest contrast-invalid condition. These late square-shaped patterns[13,23-28] were stronger in the valid condition compared to the invalid condition. In the no-report condition, the late square-shaped patterns only occurred in the high contrast-valid condition (Supplement Figure).

As with the temporal decoding analysis, we created a similar difference-AUC TGM matrix. In the report task, significant clusters emerged around 400ms after stimulus onset and ended around 500ms in both high and medium contrast conditions (Supplement Figure, all $p_{cluster} < 0.05$). In the no-report task, significant clusters emerged around 400ms and ended around 700ms after stimulus onset in only high contrast conditions (Supplement Figure, all $p_{cluster} < 0.05$).

Interestingly, in both analyses, the no-report high contrast condition contributed the longest significant time courses in the difference-AUC analysis, indicating an even longer-lasting retro-cueing perception effect.

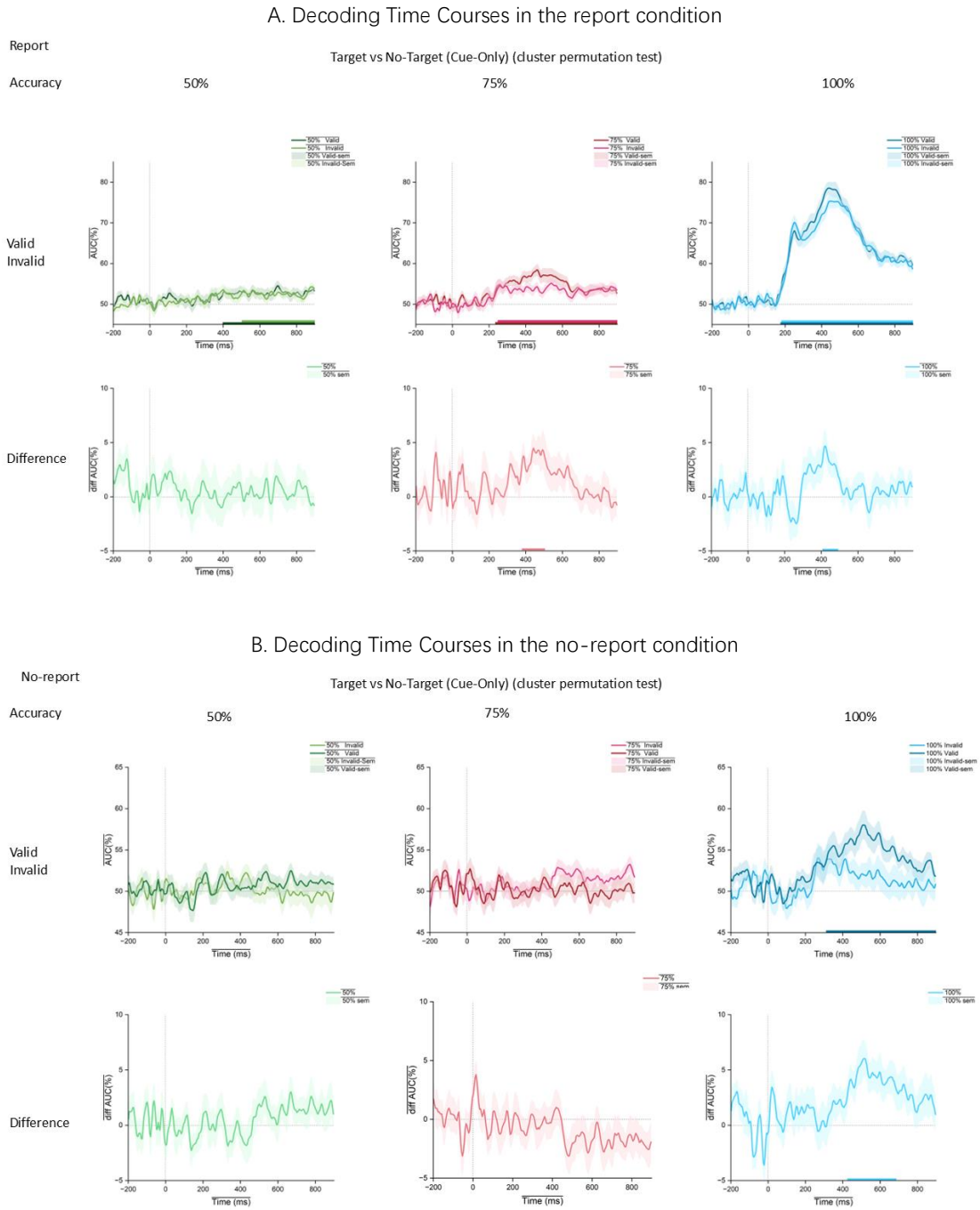
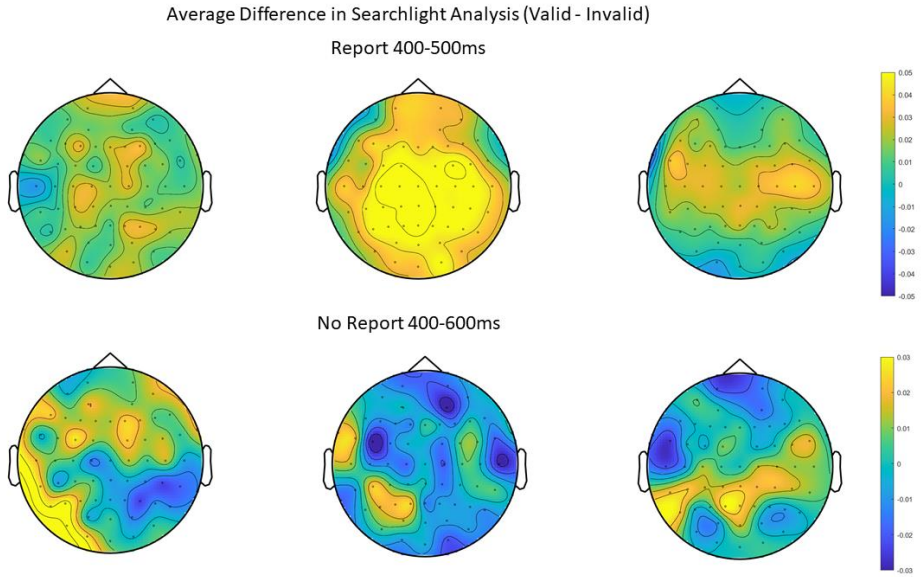


Figure 9. Decoding Time Courses in experiment3

Decoding time courses in the report condition **(A)** and the no-report condition **(B)** (target present vs. target absent) were analyzed. All nine conditions (3 contrasts: 50%, 75%, 100% × 3 congruencies: valid, invalid, difference (valid-invalid)) were plotted, with decoding performance (AUC) shown as a function of time. The top row represents the valid and invalid condition, and the bottom row shows the difference: valid minus invalid condition. Color bars indicate significant clusters identified by cluster-based permutations, p corrected <0.05.

A. Average difference in searchlight analysis in the report and no-report condition



B. Average difference in Time generalization analysis in the report and no-report condition

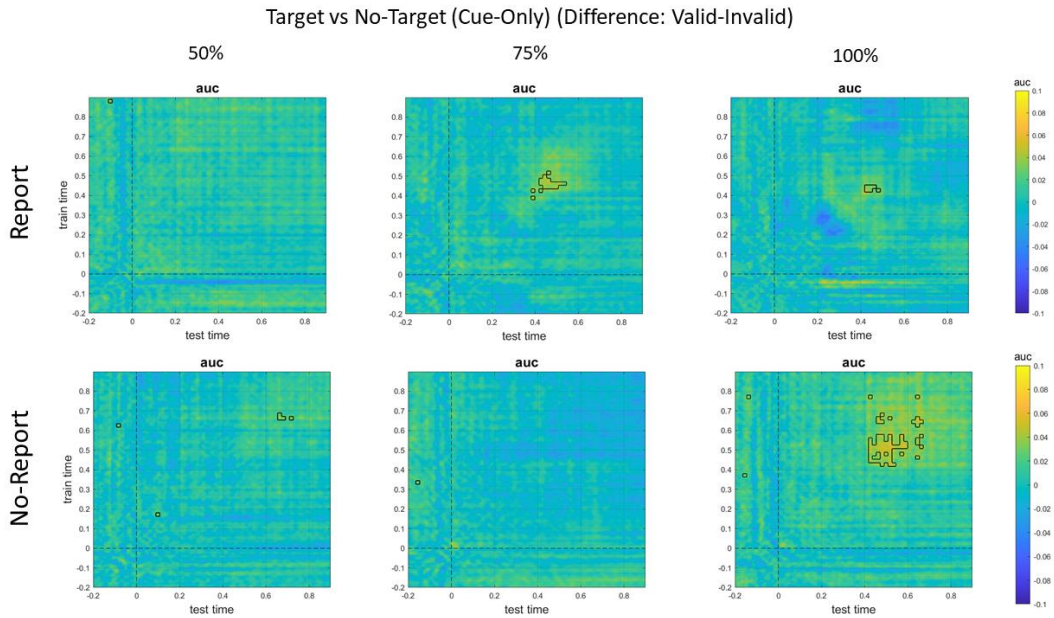


Figure 10. Searchlight Analysis and Temporal Generalization Analysis in experiment3

(A) Searchlight Analysis results for the report condition (top) between 400 and 500ms and the no-report condition between 400 and 600ms. All six conditions (3 contrasts: 50%, 75%, 100% × difference (valid-invalid) × 2 (report no-report)) were plotted, with decoding performance (AUC) shown as a function of time. The top row represents the report condition, and the bottom row shows the no-report (All images display differences in decoding performances (valid – invalid)). Color bars indicate decoding performances.

(B) A decoder was trained to discriminate between target-present and target-absent trials from 0 to 900 ms. In the report

condition and the no-report condition, all six conditions (3 contrasts: 50%, 75%, 100% × difference (valid-invalid)) × 2 (report no-report) with the decoding temporal generalization matrix (TGM). The top row represents the report condition, and the bottom row shows the no-report (All images display differences in decoding performances (valid – invalid)). Black contours indicate periods where classification deviated significantly from chance at p corrected < 0.01 (FDR).

DISCUSSION

The aim of this study was to dissociate two types of retrospective attention effects: those based on local visual sensory interaction mechanisms and those rooted in attention mechanisms. Additionally, we sought to distinguish between conscious perception and motor activity to confirm that the observed retro-cueing effect indeed enhances participants' conscious perception of the target at the neural level. To address these objectives, we conducted three experiments. In line with previous research by Sergent et al.[8], participants were asked to report a single target Gabor patch shortly after its presentation (within 1.5 seconds), ensuring no ambiguity regarding its location.

The N2pc is associated with the subliminal retro-cueing effect.

In our first experiment, we successfully replicated Sergent et al.'s[8] findings using a visible cue condition and observed a retro-cueing attention effect in the orientation discrimination task at a 66.7 ms target-cue stimulus onset asynchrony (SOA). Notably, this effect persisted even with invisible cues. Our second experiment, utilizing EEG recordings, further validated these findings. Analysis of the classic attentional ERP component N2pc revealed significant differences between valid, no-cue, and invalid conditions. This neural signature demonstrates that subliminal cues can enhance exogenous attention toward the target. Additionally, by manipulating mask intensity, we successfully dissociated two types of retrospective attention effects, aligning with similar time windows observed in previous research[7].

While prior studies have examined N2pc in subliminal cueing effects[10,30], they primarily focused on N2pc elicited by cues rather than targets. In our second experiment, we observed significant differences in target-elicited N2pc, indicating improved target attention facilitated by subliminal retro-cues. This component can be employed in subsequent studies on subliminal spatial cueing attention, particularly in research investigating subliminal retro-cueing effects.

The controversy on P3b and VAN.

In the realm of consciousness research, one of the most critical questions concerns the neural correlates of consciousness (NCC)[1,29,30]. Previous studies have intensely debated whether P3b and VAN are neural correlates of consciousness[11,19,31,32]. In classical report paradigms, P3b was considered a consciousness-related ERP component. However, recent no-report paradigm studies suggest that P3b may instead reflect motor preparation potentials related to task-specific button pressing, thereby excluding it as a candidate for NCC. Conversely, in a recent auditory study, Sergent et al. identified a new late negative component during the P3b time window under no-report conditions, with its amplitude correlating with linear stimulus intensity increases. These divergent findings add complexity to the debate, and a recent preprint by Cohen proposed that N2 is the neural marker of consciousness[13].

Under no-report conditions, our study produced results that contradict previous findings[6,13,18,19,30,32,33]: within the 300–600 ms time window, the P3b component was still present under high-contrast

conditions, albeit more attenuated compared to the report condition (Figure 7A). Although high-contrast Gabor stimuli evoked higher P3b amplitudes than low-contrast stimuli, the difference between them was not statistically significant (Figure 7A). Furthermore, our multivariate pattern analysis revealed late-stage successful decoding and metastable representations related to conscious perception occurring after 300 ms under both attention conditions in high-contrast settings.

Based on these findings, we contend that prior conclusions regarding conscious perception derived from no-report paradigms warrant skepticism. Firstly, except for experiments incorporating eye-tracking measurements, previous studies could not ensure that participants clearly perceived the experimental stimuli under no-report conditions[32,34]. Participants might achieve satisfactory behavioral performance even when their attention wavers or is diverted away from the task or screen stimuli, potentially resulting in inattentional blindness effects[35,36] that render the stimuli unconscious.

Moreover, the generalizability of using eye movement metrics to distinguish between visible and invisible stimuli from report to no-report conditions remains contentious. A recent publication highlighted that eye movement patterns do not consistently and accurately reflect the content of conscious perception[6,42].

To address these concerns, we adopted Sergent et al.'s approach from auditory perception experiments by increasing the complexity of tasks unrelated to the stimuli[37]. This included adding color discrimination tasks, mind-wandering detection, and rapid response tasks (though participants might still potentially falsify responses in mind-wandering detection questions). These measures were implemented to ensure that participants' attention remained as focused as possible on the screen.

Our results challenge the simplistic exclusion of P3b from the neural correlates of consciousness (NCC)[6,18-20,31,33,34]. The findings suggest that P3b may still play a role in conscious perception even under no-report conditions, challenging the notion that it solely reflects motor preparation potentials related to task-specific actions[6,18-20,31,33,34]. This underscores the complexity of identifying definitive neural markers of consciousness and highlights the necessity for more nuanced experimental designs that rigorously control for attention and perception.

However, alternative interpretations of our experimental results remain possible: Complex Task Design and Mind-Wandering Detection: The intricate task design, along with the introduction of mind-wandering detection tasks, may have led participants to adopt covert report strategies. Frequency of Key Presses: The number of trials requiring key presses exceeded those that did not, resulting in participants predominantly employing motor preparation strategies in most trials. Consequently, motor preparation-related potentials were not fully excluded.

Our Responses to These Concerns Are as Follows: Mitigating Internal Reporting Strategies: Half of our participants experienced the experimental sequence by performing the no-report task before the report task. Since participants were unaware of the specific tasks required in the report condition, this effectively prevented them from adopting covert report strategies. Furthermore, separate analyses of participants who performed the no-report task first did not reveal any significant differences compared to the overall results. Eliminating Motor Preparation-Related Potentials: In the no-report task, participants were instructed to make responses that were entirely unrelated to the visual stimuli, and the presentation order was appropriately balanced to avoid systematic biases. More importantly, the ERP amplitudes we present were derived by subtracting

the blank-cue condition from the target-cue condition. This subtraction method effectively mitigated components related to key responses. Additionally, in the no-report task, participants were not required to report the visibility of the Gabor stimuli. Despite this, the P3b component still appeared exclusively in the high-contrast valid conditions and exhibited higher decoding levels within the same time window. This observation aligns with characteristics reported in studies on the neural correlates of consciousness, such as the emergence of bifurcation patterns with linearly increasing stimulus intensity and decoding temporal generalization within corresponding time windows.

Retrospective attention as a trigger for conscious perception

To determine whether retrospective attention can indeed enhance conscious perception[4,6,8,11] across a broader range of physical stimulation intensities, we conducted the third experiment. If no significant neural signature differences were observed between valid and invalid conditions in the no-report task, it would suggest that retrospective attention primarily enhances attention directed at the target rather than conscious perception. Conversely, an increase in the amplitude of the ERP component associated with conscious perception, or improved brain decoding performance and advanced decoding time for the target Gabor patch with post-cueing attention, regardless of reporting, would indicate enhanced conscious perception.

The present results corroborate previous findings on the retrospective effects of attention on conscious perception observed by other researchers[4,8]. Notably, the subjective visibility results demonstrated a significant post-cue effect across low, medium, and high contrast levels, a finding not paralleled by accuracy measurements in the orientation discrimination task. This discrepancy could be attributed to the subjective measurement's heightened sensitivity compared to the objective measurement, which may be susceptible to ceiling and floor effects. While prior studies primarily employed behavioral experiments to verify the effects on conscious perception, this study rigorously tested these effects at the neural level, particularly through multivariate pattern analysis. Multivariate pattern analysis, particularly temporal generalization analysis, has primarily been applied in conscious perception experiments involving linearly increasing physical intensities. However, Mathieu Landry and colleagues recently employed this method to discriminate between the neural signatures of exogenous and endogenous spatial cueing attention.[38] Their study elegantly demonstrated how multivariate pattern analysis could corroborate earlier observations made using behavioural and ERP measures. In the present study, we adopted a similar strategy to investigate the effects of retrospective attention at the neural level. A comparison of 12 different conditions confirmed that retrospective cueing attention can indeed improve the conscious perception of Gabor patches. The decoding performance revealed a distinct pattern, showing that the benefits of retro-cued attention were due to an enhancement of the neural signature of consciousness during later time courses (400-700 ms), as indicated by previous studies[13,23-28]. (Fig 9, 10, 11).

These findings dismiss the hypothesis that the retrospective attention effect arises from memory rather than a perceptual effect. If retro-perception merely prevented the rapid decay of seen representations in memory, we would have observed no significant difference in neural signals between valid retro-cue trials and invalid or no-cue trials in the no-report task, since post-perceptual processes were excluded in this design and no stimulus is required to be memorized. However, the data showed clear evidence of enhancement in neural signals. Contrary to the widely

held assumption that events occurring after the disappearance of a stimulus affect only post-perceptual processes, such as decision-making or working memory[39-42], our results demonstrate that retro-cued attention can directly influence whether a stimulus is consciously perceived at the neural level, consistent with a recent study on retrospective perception that used a mixed model analysis approach[4].

The relationship between attention and consciousness

Contemporary theories on the relationship between attention and consciousness propose three main perspectives[43]: Double Dissociation between Attention and Consciousness[44]: This view asserts that attention can modulate sensory processing even without conscious perception, while conscious experiences can and do occur without attention. Single Dissociation between Attention and Consciousness: This stance maintains that while attention can modulate sensory processing regardless of conscious perception, conscious awareness requires attention. In other words, attention and consciousness are distinct mental processes - attention can operate independently of consciousness, but not vice versa. Attention is necessary for consciousness. No Dissociation: The third perspective opposes any type of dissociation, proposing that consciousness is attention. The first perspective is supported by the Recurrent Processing Theory (RPT), while the last two are mainly advocated by the Global Neuronal Workspace Theory (GNWT).

Our current research data supports the single dissociation perspective between attention and consciousness. In Experiments 1 and 2, we demonstrated that retrospective attention can modulate sensory processing under unconscious conditions. Furthermore, in Experiment 3, retrospective attention could still modulate conscious perception in high-contrast conditions even under no-report paradigms, indicating that attention continues to play a role in conscious perception even after controlling for decision-making and motor-related neural activities.

Notably, we employed a retro-cueing spatial attention paradigm[45], which revealed that spatial attention can modulate consciousness in purely perceptual conditions even 67ms after target presentation. This demonstrates a highly flexible temporal window for attentional modulation of consciousness, providing compelling experimental evidence for the single dissociation perspective.

Searchlight and neural correlates of consciousness

The Searchlight Decoding Analysis in Experiment 3 revealed distinct neural patterns associated with the Report and No-report conditions under valid and invalid scenarios across varying Gabor contrasts. In the Report condition, the highest decoding performance clusters were consistently localized within the fronto-parietal regions, particularly under medium and high contrast conditions (Figure 10 A). This localization suggests that the fronto-parietal network, known for its role in attention and decision-making processes, is actively engaged when participants are required to report their perceptions, especially when the visual stimuli are more salient. In contrast, the No-report condition demonstrated peak decoding performance near the occipital areas, notably under high contrast conditions (Figure 10 A). This parieto-occipital dominance aligns with the primary visual processing functions of the occipital lobe, indicating that in the absence of a reporting task, neural activity remains more confined to sensory processing regions, consistent with previous research on consciousness[6,46-48]. The shift from fronto-parietal to occipital regions between Report and No-report conditions highlights the modulatory effect of task demands on neural engagement. Specifically, the requirement to report appears to recruit higher-order

cognitive networks beyond primary sensory areas, whereas the No-report condition allows for more localized sensory processing. These findings underscore the dynamic interplay between attention, perception, and executive functions, and suggest that task instructions can significantly influence the spatial distribution of neural decoding performance.

Although late components in ERP, time decoding, and time generalization analyses are capable of decoding attention and consciousness, our Searchlight Decoding Analysis within the late time window (400 ms–600 ms) still indicates that, under no-report conditions, the decoding locations for attention and consciousness remain near posterior brain regions rather than encompassing the whole brain or the prefrontal cortex. However, due to the low spatial resolution of EEG, we are unable to accurately localize the cortical sources of these decoding signals. Therefore, these findings warrant further investigation using higher spatial resolution techniques, such as fMRI and iEEG.

Limitations of the study

It is noteworthy that in the no-report task, we only observed the retrospective attention effect in the high-contrast condition. This may be due to our use of an adapted Posner Cueing Paradigm[45], which is typically employed in spatial attention research rather than studies on consciousness. As a result, participants were required to divide their attention between two locations simultaneously. In the no-report task, however, participants were asked to perform a task entirely unrelated to the stimulus, thus allocating less attention to the target stimulus. Consequently, the contrast threshold for the Gabor patches may have increased. This is evident in the medium contrast condition, where the decoding performance in the invalid condition was higher than in the valid condition (Figs. 8, 10) when attention was not fully focused on the Gabor task. In other words, the cue presented at the same location produced an interference effect—similar to a backward masking effect[14,15,37].

Previous studies on the bifurcation model of consciousness have generally employed stimuli with the same physical intensity in both report and no-report tasks[17,18], and this study followed that approach as well. In the field of consciousness research, some researchers have used eye movement measurements[48-50] to ensure that physical stimuli are visible even when participants do not provide explicit reports. Therefore, in future studies on the retrospective spatial cueing effect, it would be advisable to include eye movement measurements to ensure that participants' subjective visibility in no-report tasks does not significantly differ from their visibility in report tasks. However, a more recent review[51] suggests that eye movement patterns do not always accurately reflect the content of conscious perception and can sometimes significantly diverge from it[6,42]. Additionally, although we controlled for the sequence effects of the report and no-report tasks (see Methods), we did not specifically examine the potential impact of the order of these sessions, which has been rigorously tested in a previous study[12]. Lastly, we did not investigate potential sex/gender differences in retrospective attention effects, which could be a valuable avenue for future research.

Future Directions and Practical Implications

Building on our findings, future research should explore the incorporation of eye-tracking measures alongside retro-cueing paradigms to better ascertain the relationship between attention and conscious perception. Additionally, investigating sex/gender differences could provide deeper

insights into the generalizability of retrospective attention effects. Expanding the range of task complexities and stimulus types could also help in understanding the boundaries of retrospective attention effects.

From a practical standpoint, our findings have potential applications in areas such as attention training programs and cognitive rehabilitation therapies. Enhancing conscious perception through retrospective attention could aid individuals with attentional deficits or those recovering from cognitive impairments. Furthermore, understanding the neural mechanisms underlying attention and consciousness can inform the development of neurofeedback and brain-computer interface technologies aimed at optimizing cognitive performance.

In conclusion, this study provides robust evidence that retrospective attention can enhance conscious perception at the neural level, distinguishing between sensory interaction and attentional mechanisms. By demonstrating that subliminal retro-cues modulate both N2pc and P3b components, we highlight the intricate relationship between attention and consciousness. Our findings support the single dissociation perspective, suggesting that while attention can operate independently, it is a necessary component for conscious awareness. These insights contribute to the ongoing discourse on the neural correlates of consciousness and theories of consciousness and pave the way for future investigations into the complex interplay between attention, perception, and consciousness.

STAR METHODS

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Xilin Zhang (xlzhang@m.scnu.edu.cn).

Materials availability

This study did not generate new unique reagents.

Data and code availability

Freely available software and algorithms used for analyses are listed in the resource table. The anonymized datasets for this study are available at Open Science Framework, https://osf.io/ This paper does not report any original code. Any information required to reanalyze the data reported in this paper is available from the lead contact upon request.

EXPERIMENTAL MODEL AND STUDY PARTICIPANT DETAILS

A total of 29 human subjects (9 male, 18–28 years old) were involved in the Experiments 1, Standard Deviation = 2.94. Twenty-four of them participated in the Experiments 1. 23 human subjects (9 male, 18–29 years old) participated in the Experiments 2 but one subject in the Experiments 2 was excluded because of too many artifacts (>10% trials was discarded). 20 human subjects (9 male, 18–29 years old) participated in the Experiments 3 and no subject was excluded. The sample size was based on the previous study regarding retro-cueing attention and a priori power calculation using G*Power program. The power analysis indicated that a sample of 24, 23 and 20 in our behavioral and EEG experiments, respectively, would be sufficient to detect a medium-size effect (f = 0.35) in a within-subjects analysis of ANOVA with the power of 0.8. They were naive to the purpose of the study except for one subject in Experiments 3(One of the authors). They were right-handed, reported normal or corrected-to-normal vision, and

had no known neurological or visual disorders. They gave written, informed consent, and our procedures and protocols were approved by the human subjects review committee of School of Psychology at South China Normal University.

METHOD DETAILS

Stimuli

In both the Experiments 1 and Experiments 2, the stimuli consisted of two horizontally arranged black circles (1.3 cd/m², 3° visual angle in diameter) on the screen, along with a central fixation cross (1.3 cd/m², 0.5° visual angle) for fixation. These circles were positioned 5° to the left and right of the fixation point. The experimental procedure was divided into a threshold testing phase and a formal experiment phase. Cues were briefly presented (16.67 ms) as a dimming (20 cd/m²) of one of the two black circles, followed by a longer dimming (83.33 ms) of both circles (with brightness adjusted for each participant) to mask the cue in the Invisible Cue conditions. In the Visible Cue conditions, there was no dimming, and a fixation screen was shown instead. The target stimulus was a Gabor patch (2° visual angle in diameter) tilted either 30° or 150° from the vertical. In Experiments 3, the stimuli were similar to those in the Experiments 1 and Experiments 2, with the following adjustments: the diameter of the black circles was increased to 4° visual angle, and the diameter of the Gabor patch was increased to 3° visual angle. Additionally, the two black circles were positioned 5° above and below the fixation point, rather than to the sides.

Behavioral experiments Overview

The experiment was programmed using Psychtoolbox based on Matlab2016b. All stimuli were presented on a 19-inch LED computer screen with a resolution of 1024×768 and a refresh rate of 60 Hz. The background was gray (28 cd/m²).

In the Experiments 1, two horizontally arranged black circles (1.3 cd/m², 3° visual angle in diameter) were always present on the screen. In Experiments 2, the black circles on the left and right sides were shifted downward by 2.5° of visual angle compared to the Experiments 1. In Experiments 3, two vertically arranged black circles (1.3 cd/m², 4° visual angle in diameter) were used instead. A fixation cross (1.3 cd/m², 0.5° visual angle) was used for fixation.

In the Experiments 1 and Experiments 2, the black circles were positioned 5° to the left and right of the fixation point. In Experiments 3, the black circles were positioned 5° above and below the fixation point. The viewing distance was 57 cm, and participants' head positions were stabilized using a chin rest. The black fixation cross was always displayed at the center of the screen.

Threshold measurement task

Before each Retro-Cueing Spatial Attention (RCSA) task, participants first performed a two-alternative forced-choice (2AFC) judgment to determine the location of the cue stimulus—either to the left or right of the fixation point in the Experiments 1 and Experiments 2, or above or below in Experiments 3. Accuracy in the visible cue condition was maintained above 95%, while in the invisible cue condition, it was kept at 50%, i.e., chance level. Following this, we measured the orientation discrimination thresholds of the target Gabor using a 2AFC staircase procedure aimed at achieving 75% accuracy. This was done to ensure equal performance across both visible and invisible cue conditions. The stimuli and procedure for this threshold measurement task were identical to those of the RCSA task, except that no cue stimuli were presented. The contrast

discrimination threshold measurement task consisted of two sessions: one for the visible condition (without a Mask stimulus) and one for the invisible condition (with a Mask stimulus). The order of these sessions was counterbalanced across participants. Each session included two staircases of 80 trials each. Each trial began with a central fixation point. Participants were instructed to press one of two buttons to indicate the orientation of the target Gabor. The contrast of the target Gabor varied from trial to trial and was controlled by the staircase procedure to estimate the participants' orientation discrimination threshold at a 75% correct level.

Experiment1

Each participant completed four staircase sessions (80 trials each): two for the visible cue condition and two for the invisible cue condition. These sessions determined the target's contrast at which participants could discriminate the target's orientation with 75% accuracy, without any attentional manipulation. This contrast value was then fixed for the remainder of the experiment. Participants subsequently performed four experimental blocks, each consisting of 288 trials, resulting in 96 trials for each combination of cueing and SOA conditions.

As shown in Figure 1A, each trial commenced with the appearance of a fixation cross at the center. After a random delay of 800 to 1200 ms, a target—a Gabor patch with a random orientation (30° or 150° away from the vertical)—was displayed for 33.33 ms within one of the circles located to the left or right of the fixation point. The target contrast was individually calibrated for each participant using a staircase method. A 16.67 ms cue, consisting of a brief dimming of one of the circles, could appear either before or after the target. This cue could be either valid (on the same side as the target) or invalid (on the opposite side). Following the cue, there was an 83.33 ms mask or fixation period for the invisible and visible conditions, respectively.

A response screen was presented 800 to 1200 ms after the offset of the mask or fixation, with a response cue indicating the target's side (marked by a thickening and dimming on one side of the cross). Participants were then asked to report the target's orientation by choosing between two options (Left/Right). Subsequently, a second response screen appeared, displaying a dimming cross at the fixation point, where participants reported the position of the cue in a two-alternative forced choice (2AFC) task.

Experiment2

Each participant completed two staircase sessions (80 trials each) for the invisible cue condition to determine the target's contrast at which they could discriminate the target's orientation with 75% accuracy, without any attentional manipulation. This contrast value was then fixed for the remainder of the experiment. Participants subsequently performed four experimental blocks, each consisting of 153 trials, resulting in 136 trials for each cueing condition, including the non-cue condition and catch trials (33.33%).

As shown in Figure 1B, the stimulus presentation for the EEG experiment was consistent with that of the Experiments 1. The procedure in Experiments 2 was fundamentally similar to the Experiments 1, with the following modifications: the two circles were placed below the fixation point (shifted downward by 2.5° of visual angle compared to the Experiments 1); the target presentation screen included a fixation screen with a 33.33% probability (catch trials); the stimulus

onset asynchrony (SOA) between the target and the cue was fixed at 66.67 ms; a Non-Cue condition was added to the cue presentation; and only the mask stimulus was presented, thereby maintaining only the invisible condition.

Experiment3

Each participant completed six staircase sessions (80 trials each) for the visible cue condition to determine the target's contrast at which they could discriminate the target's orientation with 50%, 75%, and 100% accuracy, without any attentional manipulation. These determined contrast values were then fixed for the remainder of the experiment. Participants subsequently performed four experimental blocks, each consisting of 196 trials, resulting in 112 trials for each cueing condition, including the catch trials (25%).

As shown in Figure 1C, in this experiment, two circles were positioned above and below the fixation point. The Gabor patch and the cue randomly appeared in one of the two circles. The physical stimulus intensity was determined for each participant based on the Gabor contrast levels obtained from the staircase test: high contrast for near 100% orientation discrimination accuracy, medium contrast for approximately 75% accuracy, and low contrast for about 50% accuracy. The fixation screen from Experiments 2 was retained for catch trials.

As shown in Figure 1D, on the response screen, the active reporting condition remained similar to the Gabor patch orientation discrimination task from the previous experiment. However, participants were now required to identify both the orientation of the Gabor patch (Left or Right) and rate the subjective visibility ("visible" or "invisible") simultaneously. Thus, in each trial, participants had four response options.

Additionally, a passive viewing condition was introduced, wherein participants were required to complete one of three randomly presented tasks:

1. Speed Response Task: Press the SPACE key whenever a green cross was displayed at fixation.
2. Mind-Wandering Detection Task: Participants answered the question "What is on your mind just now?" by choosing one of four options: "the Gabor/Fixation," "the cross," "my thoughts," or "nothing/I feel sleepy."
3. A Simple Message Prompting: "Press SPACE to continue."

EEG data Acquisition

Sixty-four electrodes were placed according to the international 10-20 system to collect EEG data, using the Brain Products EEG amplifier (Brain Products, Munich, Germany) for signal amplification. During recording, the impedance of all electrodes was kept below 10 kΩ. The frontal electrode FCz served as the online reference point, while the electrode AFz served as the ground. No online filtering was applied to the electrodes, and continuous sampling was performed at a frequency of 1000 Hz per channel. Eye movements and blinks were monitored using the IO channel located under the right eye.

Data Preprocessing

Offline preprocessing of EEG data was performed using BrainVision Analyzer 2.2 (Brain Products) and the EEGLAB toolbox[52]. Firstly, visual identification of any noisy electrodes was performed, and interpolation of surrounding electrodes was used to reconstruct the noisy channels if necessary. All electrodes were then re-referenced to the average of the left and right mastoids. Then, all EEG

signals underwent a series of filters: 0.1 Hz high-pass, 25 Hz low-pass, and 50 Hz notch filtering with a 24 dB/Oct roll-off. Vertical eye blink correction and horizontal eye drift correction were also applied. Segmentation of trials around the target (or the same time point in cue-mask-only trials). Segments containing peak-to-peak deviations exceeding ±70 µV were excluded from the analysis, and if the number of excluded segments exceeded 20% of the total trials, the data from that participant were discarded. Baseline correction using the time window from -100 to 0ms pre-stimulus.

ERPs and cue, cue-mask subtraction

Trials were sorted by condition and trial type (valid, invalid, or cue/cue-mask only). Each group of trials was averaged at the participant level and low-pass filtered at 25 Hz. To isolate stimulus-related neural activity from cue/cue-mask-evoked activity, the cue/cue-mask-only ERPs were time-shifted to align the timing of the cues with cue onset in the stimulus-cue-mask trials, following the procedure of Del Cul and Cohen[13,17]. This was done for each condition, and the time-shifted mask ERPs were subtracted from the corresponding stimulus-cue-mask ERPs as follows:

The cue/cue-mask-only ERP is initially time-locked to cue onset (i.e., time 0 is when the first cue was presented).

The cue/cue-mask-only ERP is then shifted forward in time so that cue onset aligns with cue onset in each of the stimulus-cue-mask ERPs.

The time-shifted mask ERPs are subtracted from the corresponding stimulus-cue-mask ERPs.

ERP analysis

Three ERPs of interest were identified based on data from the initial group: the N2pc in Experiments 2, the VAN in Experiments 3 (both displaying bifurcation dynamics in the no-report condition), and the P3b (displaying bifurcation dynamics in the report condition). The following time windows and electrodes were selected for each component and pre-registered on OSF (nearest channels of the international 10-20 system are reported in parentheses):

N2pc: 240-280 ms, electrodes 9, 42, 56 (O1/O2, PO3/PO4, PO7/PO8).

P3b: 300-600 ms, electrodes 1, 4-6, 13-15 (Pz, P1, P2, CPz, CP1, CP2, Cz).

VAN: 240-280 ms, electrodes 9, 10, 42, 43, 56, 57 (P5, P6, P7, P8, PO7, PO8)

These time windows and electrodes were used for all analyses of these three ERPs. Additionally, a post-hoc analysis of the **VAN** was conducted, measured from **240-280** ms at electrodes 9, 10, 42, 43, 56, 57 (P5, P6, P7, P8, PO7, PO8).

Multivariate pattern analysis

All decoding was conducted using the MVPA-Light toolbox[20] and fieldtrip[53] for MATLAB. Data was exported from BrainVision Analyzer and formatted for use with the MVPA-Light toolbox using EEGLAB. For each cue validity and task condition, a linear classifier (LDA) was trained to distinguish between stimulus-present and cue-mask-only trials using a 9-fold cross-validation procedure.

At each time point, the decoder was first trained on 8/9 of the trials and then tested on the remaining subset of trials. This process was repeated nine times, ensuring that the decoder was both trained and tested on the entire dataset over the course of the procedure. Importantly, the classifier was never tested on data used for training when assessing performance.

Trial numbers were balanced across classes so that there were equal numbers of stimulus-present

and cue-mask-only trials in each fold. Classifier sensitivity, summarized as the area under the receiver operating characteristic curve (AUC), was averaged across the folds to calculate overall classifier performance.

Temporal generalization

The temporal generalization analysis technique characterizes the neural dynamics of perceptual representations by testing if a classifier trained on data from one time point can successfully discriminate between classes when applied to data from different time points. If a classifier trained at time T1 is able to decode stimulus presence at a level significantly above chance when tested at time T2, it suggests that the neural dynamics supporting above-chance decoding at T1 are recurring at T2.

Temporal generalization matrices were computed by training classifiers on one time point and testing each at every other time point. Classification sensitivity was statistically tested against chance and corrected for multiple comparisons using 1000-permutation cluster-based permutation testing.

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