Supplemental Information

Cueing attention after the stimulus is gone can retrospectively trigger conscious perception.

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**Figure S1**: Sensitivity (d’), bias (c) and reaction times in Experiments 1 and 2 (complements performance presented in Figures 1 and 3):

Categorizing the responses options as “right tilted” or “left tilted” allowed separating sensitivity (A and C) and bias towards choosing the left tilted or right tilted response option (B and D), using the measures d’ and c from signal detection theory. (A) Congruent cues improved sensitivity compared to incongruent cues (Congruency: $F(1,17) = 24.7, p < 0.0001$; SOA: $F(3.6,61.6) = 3.87, p < 0.01$; Congruency×SOA: $F(3.5,60.2) = 2.9, p < 0.03$). (B) Bias was not different for congruent or incongruent cues (Congruency: $F(1,17) = 1.2, p = 0.30$). (C) Congruent cues globally improved sensitivity compared to bilateral cues (Congruency: $F(1,17) = 5.1, p < 0.03$). (D) Bias was not different for congruent or bilateral cues (Congruency: $F(1,17) = 2.8, p = 0.13$). (E-F) Acceleration in reaction times for congruent versus incongruent cues paralleled the improvement in performance, confirming the absence of a speed-accuracy tradeoff (Figure 1.B and Figure 3.A). Shown here are median reaction times (RTs) in the orientation discrimination task computed for each participant and then averaged across participants. These RTs are calculated from the onset of the response screen. (E) RTs in Experiment 1 (Congruency: $F(1,17) = 20.6, p < 0.0001$; SOA: $F(3.3,56.1) = 21.1, p < 0.0001$; Congruency×SOA: $F(3.2,54.7) = 2.5, p = 0.064$). (F) RTs in Experiment 2 (Congruency: $F(1,17) = 20.5, p < 0.0001$; SOA: $F(1.5,24.9) = 25.8, p < 0.0001$; Congruency×SOA: $F(1.8,31.2) = 0.7, p = 0.48$). Error bars represent standard error of the mean effect size. Significance on post-hoc t-tests: *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.005$. Note that the effect of 200 ms post-cues in (A) was marginally significant on post-hoc ($p = 0.051$).
Supplemental Figure S2

Figure S2: Replication of the results in a control experiment using cues with different low-level characteristics (complements Figure 2)
(A) illustrates the physical changes that have been introduced in the placeholders and cues in the control experiment. (B) The results of the control experiment replicated the effects observed in experiments 1 and 2: despite important changes to low-level characteristics of the cue, congruent pre-cues and post-cues still drove a very substantial improvement in orientation discrimination. Error bars represent standard error of the mean effect size. Significance on post-hoc t-tests: * : p < 0.05; ** : p < 0.01; *** : p < 0.005.
Supplemental Figure S3: Relationship between objective and subjective measures in Experiment 2 (complements Figure 3). The correspondence between subjective visibility ratings (0% is “not seen”, 100% is “maximal visibility”) and associated objective performance on orientation discrimination was the same for congruent and incongruent cues at all SOAs (no significant differences as assessed by t-tests at each subjective visibility level). 50% is chance level, 80% is the baseline average performance in the absence of cueing. In all graphs, error bars represent standard error of the mean effect size. Significance on post-hoc t-tests: *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.005$. 
Supplemental Figure S4

**Figure S4:** Illustration of the model fit in three representative participants with different response profiles (complements Figure 4). (A), (B) and (C) are three different participants (Subjects 8, 9 and 18 respectively). For each participant, the column on the left shows the response distributions obtained in the two “template” conditions (bottom: target absent; top: target present and “seen”). All three subjects showed similar response profiles for target absent, but had slightly different response profiles for target present and “seen”: response distribution peaked around 50% in (A), around 85% in (B) and 70% in (C). The right column shows, in black, the response distribution obtained for each subject in a different condition, independent from the templates (congruent post-cue at SOA = 100 ms). In every case, this distribution was accurately modeled by a mixture of both template distributions. In particular, the differences in peak values in the high visibility range was preserved across the different subjects.
Supplemental Table S1

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<th>Incongruent cue</th>
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Supplemental Table S1: Model fit of the response distributions obtained on the subjective visibility scale in every experimental condition for each participant (complements Figure 4). This table shows the coefficient $r^2$ of the regression for each subject. This coefficient is shown in red if regression is significant at $p < 0.01$, and in pink if regression is significant at $p < 0.05$. There were only 2 participants for which the model did not significantly account for the response distribution in every experimental condition. Note that the templates for the regression are not independent from the data modelled in the leftmost column (congruent cue at -100 ms); while independence is preserved for the other conditions.
Supplemental Experimental Procedures

Observers. A total of 62 observers were recruited for these experiments (experiments 1 and 2: 20 observers each; control experiment: 22 observers). Five subjects were discarded from the analysis because of too many eye movements (as assessed by online electro-occulogram) and/or failure to perform the task. The results are thus based on 18 participants in experiment 1 (aged 25 ±4.5; 12 women; 1 left-handed), 18 in experiment 2 (aged 23 ±3.8; 14 women; 1 left-handed) and 21 in the control experiment (aged 22 ±2.2; 15 women; 2 left-handed). All had normal or corrected to normal vision. They provided informed consent. The procedure conformed to the French policy on experimentation with healthy volunteers and was approved by the local ethics comity.

Apparatus. The stimuli were generated on a PC using Matlab and the Psychophysics Toolbox (1, 2), and presented on a CRT monitor. Luminance presentation was controlled using Psychophysics Toolbox functions correcting for gamma and achieving a fine resolution in levels of gray. Refresh rate was 60 Hz. Screen resolution was 1024 by 768 pixels. Participants were seated 60 cm away from the monitor, in a dimly lit room.

Eye fixation was monitored online using EOG recording with disposable Silver/Silver Chloride electrodes (Viasys) and a Biopac amplifier (Biopac systems MP150) with a gain of 1000. For each participants, we calibrated the EOG before the actual experiment by asking them to make saccades from central fixation to targets (small Gabors) positioned at 2.5° or 5°. In all subjects we insured that we could reliably detect those 2.5° and 5° saccades away from fixation on the online EOG trace before we started the actual experiment.

Stimuli and design

Experiment 1. Stimuli were presented on a uniform grey background (28 cd/m²; Figure 1). Three black circles, aligned horizontally, were always on screen: one small circle (subtending 0.6° of visual angle) at the centre of the screen for fixation, and two larger black circles (2.4° in diameter) at 4° eccentricity to the left or to the right of fixation. These large circles indicated the locations where a target could appear. Each trial began with the onset of a black dot (0.3×0.3°) within the central circle. The dot remained onscreen until response screen. Following a random delay within 500 to 900 ms after the beginning of the trial, a target was presented for 50 ms within one of the large circles, to the left or to the right of fixation. It was a Gabor patch subtending 2° in diameter (2 cycles per degree, 1° full width half maximum).
The grating orientation was randomly chosen on each trial between 30 and 60 degrees or between 120 and 150 degrees, thus excluding vertical or horizontal orientations. Target’s average luminance was equal to background luminance. Its Michelson contrast was determined for each participant following a standard staircase procedure, to reach 80% accuracy on orientation discrimination in the absence of cueing (3).

A response screen was presented after a random delay (500 to 900 ms after target offset). At response screen onset, the central dot disappeared and was replaced by a thickening of one side of the central circle. This thickening always truly indicated the side where the target had been presented. In target absent trials (Experiment 2), the thickening pointed randomly to the left or the right. Participants had to base their response on what they perceived on that side.

Two response options were presented above and below fixation at 1° eccentricity. They consisted in two small Gabor patches of maximal contrast (1x1°, 4 cycles per degree, 0.5° full width half maximum), one with the same orientation as the target, the other with the orthogonal orientation. Participants reported target orientation by choosing the corresponding option, using two response buttons fixed vertically on the armchair’s arm (index and middle finger). The correct orientation was randomly presented above or below fixation. Participants had 1.5 seconds to respond. Next trial started 500 ms after response or expiry of response delay.

During experimental trials, spatial attention was cued to the left, or to the right, or both locations simultaneously ['bilateral cue’ condition, in Experiment 1 only] by a brief dimming of the left or right circle or both, which turned from black to dark gray (14 cd/m²) for 50 ms. This yielded three equiprobable and randomly intermixed cueing conditions: congruent cueing (cue and target on the same side), incongruent cueing (cue and target on opposite sides) and bilateral cueing (only in experiment 1). In randomly intermixed trials we tested 3 pre-cues SOAs at 400 ms, 200 ms and 100 ms before target, and 3 post-cue SOAs at 100, 200 or 400 ms after target, for each of the three cueing conditions.

**Experiment 2.** Experiment 2 was identical to Experiment 1 except for the following points: (1) after reporting target’s orientation, participants used a scale to report the subjective visibility of the target (2) “target absent” trials were included (28% of the total number of trials) (3) only three typical target-cue SOAs were tested: -100 ms, +100 ms and +400 ms (4) “bilateral cueing” condition was not included in this experiment.

Once participants had given their response on the orientation task —or when the time limit of 1.5 s was over— a second response screen appeared with a visibility scale at the centre (Figure 1.A). The visibility scale was similar to the one used in our previous studies (4, 5): it
was a dark gray vertical bar (1°×4°, 6 cd/m²) on which a light gray cursor (1°×0.5°, 50 cd/m²) could take 8 adjacent positions, labeled “Maximal visibility” and “Not seen” at opposite ends. Initial cursor position was random. Participants moved the cursor with the top and bottom response buttons, and validated their rating with a third button (thumb). The time limit for this task was 10 s.

**Control experiment.** A third experiment included a control for the importance of local low-level interactions between the target and cue at SOAs -400, -150, +150 and +400 ms, by introducing major changes to the physical properties of the placeholders and cues (see Supplemental Figure S2.A). The placeholder circles of experiments 1 and 2 were replaced by larger noise-textured annuli (inner diameter: 3.5°, outer diameter: 4°). The noise texture was a mixture of black and white pixels with an average luminance equal to background luminance (28 cd/m²), and a Michelson’s contrast of 100%. The cue consisted in a decrease of the texture’s contrast from 100% to 50% with no change in the texture’s average luminance. Bilateral cueing was not tested in this experiment. Congruent and incongruent cues were equiprobable. On 7% of the trials, the attentional cue was absent (“no cue” condition). The delay between target offset and response screen was random within 1.2 to 1.6 s.

**Procedure**

**Experiment 1.** Each participant completed two staircase sessions (80 trials each) to determine the target’s contrast for which they could discriminate target’s orientation with 80% accuracy in the absence of attentional manipulation. Target’s contrast was then fixed to that value for the rest of the experiment. Participants performed ten experimental blocks of 144 trials, yielding 80 trials in each condition of cueing and SOA.

**Experiment 2.** The procedure was the same as in experiment 1 except that after the two staircase sessions, which involved only the orientation discrimination task, participants trained to perform both the objective and subjective task with the low target contrast determined in the staircase. This allowed them to calibrate their use of the subjective visibility scale [see instructions for visibility scale in Supplementary Materials]. Participants performed ten experimental blocks of 84 trials, yielding 100 trials in each condition of cueing and SOA for “target present” and 40 for “target absent”.

**Control experiment.** The procedure was the same as in experiment 1, participants performed 80 trials in each condition.

**Data analysis**
Data analysis was performed in Matlab with the statistics toolbox. Statistical comparisons involved standard repeated measures ANOVAs (with a Greenhouse-Geisser correction) or post-hoc Student paired t-tests, except when otherwise stated.

**Estimation of detection sensitivity based on subjective visibility distributions (Experiment 2)**

For each participant and each experimental condition we evaluated the “receiver operating characteristics curve” for detecting the target (the function relating ‘hits’ and ‘false alarms’) by shifting an arbitrary decision criterion between the different levels of the visibility scale. For each of these arbitrary decision criteria we can determine a ‘Hit’ and a ‘False Alarm’ rate, corresponding to the proportion trials where visibility rating is above this criterion in the “target present” and in the “target absent” conditions respectively. The area under this receiver operating characteristics curve (AUC) provides detection sensitivity independently of response biases(6). In practice, we calculated this AUC using a signed rank test between the visibility ratings obtained for target present and target absent trials, in each condition and for each participant. Indeed, the U statistic of this test has been shown to be mathematically equivalent to the trapezoidal estimate of the AUC (7).

**Regression analysis of subjective visibility distributions (Experiment 2)**

For each subject individually, we tested whether it was possible to model the distribution of subjective visibility ratings obtained in each condition (denoted D below) as a balance between two other visibility distributions measured for this subject (Figure 4.C): (1) the visibility distribution obtained when the target was present in a condition with good visibility: it was congruently pre-cued and orientation was correctly reported (denoted D_seen below); and (2) the visibility distribution obtained when the target was absent in the same condition (denoted D_absent below). These distributions are vectors, containing 8 data points each, corresponding to the proportion of trials, within a particular condition, where the participant used the first level of visibility, the second level etc… until the 8th level. Importantly, D, D_absent and D_seen were data measured for each subject: the numbers within these vectors were not variables; they were not allowed to vary to fit the model. The equation of the model was: $D = \beta \times D_{seen} + (1-\beta) \times D_{absent}$, equivalent to: $D - D_{absent} = \beta \times (D_{seen} - D_{absent})$. Thus, there was only one free parameter in the model: parameter $\beta$. This parameter $\beta$ evaluated the proportion of $D_{seen}$ that contributed to $D$ if $D$ could indeed be described as being only a mixture of $D_{seen}$ and $D_{absent}$. This model was evaluated using a simple linear regression of $D - D_{absent}$ by $D_{seen} - D_{absent}$, with no constant term.
Instructions for using the subjective visibility scale

Participants had to report what they had seen on the side indicated by the thickening on the central fixation circle (which always indicated the correct position of the target in ‘target present’ trials). The instructions for using the visibility scale were inspired from the instructions we used in our previous experiments (4, 5) as well as from the Perceptual Awareness Scale (8):

- Place the cursor at the bottom of the scale if **you didn’t see anything** on the indicated side.
- If you have a **vague impression** of having seen something on the indicated side, move the cursor up from the bottom position. **The more this impression gets precise, the more you should move the cursor up.**
- Use high visibility levels above the middle when **you have seen the target. The more your perception of the target is clear and precise, the more you should move the cursor up.**
- Use the highest visibility level when **your perception of the target is maximal,** that is the clearest possible given the low contrast of the target.

Supplemental references