Supplemental Experimental Procedures

Observers

From forty-two observers with normal or corrected-to-normal vision who perceived phosphenes, 10 observers (4 female; mean age = 23 ± 4 years old) met the criterion to participate in the experiment. For inclusion, the phosphene had to be located at an eccentricity greater than 4° and subtend a diameter ≥ 2°; see **Procedure**). Observers provided written informed consent. The experimental protocol was in compliance with the safety guidelines for TMS research and was approved by the University Committee on Activities Involving Human Subjects at New York University. One of the ten observers was not included in the final analysis as this observer was unable to complete all TMS sessions due to a technical hardware issue with the TMS machine.

Stimuli

Stimuli were generated using the MATLAB software (MathWorks) in conjunction with the Psychophysics toolbox [1, 2] on a Macintosh computer. Stimuli were displayed on a high-resolution CRT monitor (53 cm; 120Hz; Professional Series P220f, ViewSonic monitor) placed 57 cm away from the observer's head. Head position was maintained using a chin rest fixed to the table. The display was calibrated and gamma corrected using a linearized lookup table. A white fixation cross (0.2° long crisscrossed diagonal lines) was presented at the center of the screen throughout the experiment. The stimuli consisted of two 5 cpd Gabor patches (i.e., contrast-defined sinusoidal gratings enveloped by a Gaussian window). The placement of the Gabor patches (eccentricity) was determined individually for each observer and calculated as the center of the perceived phosphene (see **Procedure**). The size of the Gabors was adjusted (3.8° ± 0.2° on average for all observers) according to the Cortical Magnification Factor: $M = M_o(1+.42E+.000055E^3)^{-1}$ [3, 4]. The attention and response cues (see **Procedure** and **Figure 1c**) consisted of black rectangles (0.3° long) that replaced one of the two branches of the central fixation cross pointing to the locations of the upcoming Gabor stimuli. Eye position was monitored using an infrared video camera system (Eyelink 1K, SR Research, http://www.sr-research.com/EL_1000.html) to ensure that all observers maintained fixation throughout each trial during all psychophysical and TMS sessions. Stimulus presentation was contingent upon fixation; any trials in which observers broke fixation (defined as an eye movement ≥1° from the center of the fixation cross or if the observer blinked) was cancelled and then repeated at the end of each experimental block.

TMS apparatus and Neuronavigation

Observers were stimulated using a 70mm figure-of-eight coil (double Alpha coil) positioned over the occipital cortex (handle oriented vertically, anterior to posterior). Biphasic TMS pulses were applied using a Magstim Rapid^2 Plus^1 stimulator (3.5T) (Magstim, Spring Garden Whitland, Great Britain, http://www.magstim.com/products/magnetic-stimulators), and triggered via MATLAB using a Jali Medical BNC triggering device. Stimulation threshold for each observer was defined as the percentage of TMS stimulation machine intensity under which the observer perceived a phosphene 50% of the time. Stimulation intensity remained constant throughout the entire TMS portion of the study for each observer (on average 58% ± 2% of the maximal stimulator output).

A 3D topography of each observer's head was recorded using a digital laser scanner (FASTSCAN, Polhemus, Vermont, USA, http://polhemus.com/). During each TMS session, after locating the appropriate stimulation site on the surface of the scalp (see **Phosphene Mapping procedure**), we co-registered the position of the TMS coil with the observer's 3D head image, then marked the location of the stimulation site on the surface of the scalp using equipment and software developed by Rogue Research (Brainsight, Montreal, Canada, https://www.rogue-research.com/). This neuronavigation procedure was used to ensure that we consistently stimulated the same region across sessions.

Procedure

Each observer participated in thirteen sessions: one to localize and map her/his phosphene, another to record a 3D image of her/his head (to be later used for neuronavigation) and to familiarize them with the behavioral task, six psychophysical sessions to measure their contrast response function (CRF), and five TMS sessions.

Phosphene mapping. We used the same phosphene mapping protocol as in previous studies [5, 6]. Observers continually fixated upon a dark blue fixation cross, located at the center of a black screen (**Figure 1a**). A train of 7 TMS pulses (30 Hz) at 65% of maximal output intensity was applied on the scalp over the

assumed V1/V2 region (1 cm above the inion). The stimulation train was applied either to the left or right hemisphere (~2 cm away from the midline) to induce phosphene perception either in the right or left hemifield, respectively. If a phosphene had been reported on the previous trial, observers were then asked to draw the outline of the perceived phosphene as precisely as possible using the computer mouse on the next trial. They were allowed to repeat the stimulation and verify the phosphene outline until they were satisfied with their response. This region was then used to determine the placement of the Gabor patches in both hemifields; one Gabor patch was placed inside the region corresponding to the phosphene area, so-called 'stimulated region', while the other one was placed inside the symmetrical region in the opposite hemifield ('non-stimulated region') during the subsequent behavioral task. Phosphene mapping was terminated when the spatial extent of the phosphene was large enough to encompass the entire Gabor patch; otherwise, the TMS coil was displaced by 1 cm and the procedure was repeated until a suitable phosphene was found. Once a reliable and large enough phosphene was localized, two pulses were applied (same as in the main experiment) and stimulation intensity was progressively reduced until observers reported seeing a phosphene at approximately the same location on 50% of trials. This intensity level was defined as the observer's phosphene threshold, and was the intensity of TMS stimulation during the main experiment [5-7]. The same procedure was employed during all phosphene-mapping sessions (used to determine observer eligibility) and at the beginning of each TMS session to ensure consistency in stimulation site (between-session control of the stimulated region). Phosphene drawings were highly consistent within each observer, and phosphene region locations overlapped across all TMS sessions (5 observers perceived a phosphene on the left and 5 observers perceived a phosphene on the right; **Figure 1b**).

Behavioral task. Observers performed a two-alternative forced-choice (2-AFC) orientation discrimination task (**Figure 1c**). After 100ms of fixation, a central cue was presented for 30ms; the cue indicated the location of the upcoming target in 75% of the trials ('valid cue') or the distractor in 25% of the trials ('invalid cue'). Observers were instructed to voluntarily allocate their attention to the spatial location indicated by the cue. After a 380ms inter-stimulus interval, long enough to allocate voluntary attention [8-10] two Gabors were presented for 50ms (one in the phosphene region and the other in the symmetric region, always in the lower half of the visual screen corresponding to the locations of the perceived phosphenes). Gabor tilt was adjusted between sessions (so that observers performed with ~80% accuracy overall) to equate task difficulty across multiple sessions for the same individual and between individuals (3.6° ± 0.8° was the average across all observers). Orientation of the Gabor stimuli (clockwise or counterclockwise relative to vertical) was independently and randomly chosen on every trial. At the onset of the Gabor stimuli, a response cue simultaneously appeared to indicate the target location, i.e., the stimulus for which the observers had to report the orientation (clockwise or counter-clockwise from vertical). The response cue remained on the screen for 600ms. Observers were allowed to give their answer once the response cue disappeared, within a window of 500ms. There were four possible response keys: they reported the orientation of the left Gabor patch (left key for left tilt or right key for right tilt) with their left hand, or the orientation of the right Gabor patch (left key for left tilt or right key right tilt) with their right hand. At the end of the response window, an auditory feedback tone indicated whether the observer's response was correct (high pitch), incorrect (medium pitch) or absent (low pitch). In the absence of a response from the observer, the trial was considered an error and was discarded from the analysis.

To assess contrast sensitivity, we measured task performance as a function of stimulus contrast during six psychophysical sessions. To obtain the CRF, stimulus contrast was randomly chosen from amongst one of seven possible contrast levels and varied from trial to trial. Each observer's CRF was defined as their performance [d'=z(hit rate)–z(false alarm rate)] on the orientation discrimination task across all contrast levels (ranging from 2 to 32%). A left response to a left tilted stimulus was (arbitrarily) considered a 'hit', and a left response to a right tilted stimulus was considered a 'false alarm' (the opposite assignment is mathematically equivalent). For each observer, the data was fit with a Naka-Rushton function, using a least-squares criterion, where d' is performance as a function of contrast. The large experimental stimuli were always presented at the same location within each session to eliminate location uncertainty and to encourage observers to maintain a relatively small attention field; therefore, we expected [11-13] and found a response gain change in behavioral performance with a valid attention cue compared to an invalid cue. To characterize whether and how much the TMS manipulations altered this response gain, the Gabors were always presented at the contrast level corresponding to d'max (asymptotic performance) for each observer. **Figure 1d** shows d'max for each observer for the valid and invalid trials; attention benefitted performance for each observer.

TMS sessions. Observers performed five TMS sessions (2.5h each). Each session consisted of (a) calibrating the neuronavigation system, (b) localizing the appropriate phosphene region and marking the coil location on the scalp surface, (c) determining the stimulation threshold, (d) calibrating the eye-tracking system, and (e) tracking the coil position and monitoring eye movements while observers performed the behavioral task and received TMS stimulation. The two Gabors were presented at 32%, where all observers had reached d' max. One Gabor patch was presented in the stimulated region while the other was presented

in the non-stimulated, symmetrical region relative to the fixation cross. On any given trial, either the 'target' Gabor (Gabor patch for which the observers had to report the orientation), or the 'distractor' Gabor was stimulated. This procedure enabled the comparison between target- and distractor-stimulated for valid-cue and invalid-cue trials. In these 4 conditions, which were randomly interleaved, observers received identical brain stimulation so that the sound and sensations induced by the TMS pulse were constant throughout. For these reasons, there was no need to use a sham in this experiment. Double pulses of TMS (25 ms interval) were administered at 10 different delays, either before (2 timings; -370 and -55 ms) or after stimulus onset (8 timings; 75, 125, 175, 225, 275, 325, 375, & 425 ms) (**Figure 2a**). Across the five TMS sessions, observers performed 48 trials per 40 conditions: 10 TMS delays, 2 cue conditions (valid/invalid), and 2 stimulation conditions (target-stimulated/distractor-stimulated), for a total of 1920 trials per observer. Note that no phosphenes were observed during the main experiment (confirmed by observers' reports). As the stimuli were presented on a gray screen during the TMS session, as opposed to the black screen used during the phosphene mapping, observers' sensitivity for phosphene perception was effectively decreased, i.e. the minimum intensity to invoke phosphene perception increased [14].

Behavioral analysis. For the analysis, the valid trials were sub-sampled so that there were an equal number of trials in the valid and invalid conditions for each observer. This allowed for a fair comparison (same power) between the two conditions (note that for all analyses, we observed the same pattern of results when considering the full data set–not shown). This sub-sampling was performed 1,000 times, and the repetitions were then averaged to obtain d' differences at different delays relative to stimulus presentation. The error bars represent ±1 SEM computed after removing each observer's global mean across conditions, and then scaled by J/(J-1), where J is the number of within-subject conditions (2x2x10) in the analysis [15]. To test the hypothesis that attentional reorienting is periodically modulated at a low frequency, a Fast Fourier Transform analysis was applied to obtain the amplitude spectrum of the TMS-induced d' difference between target-stimulated and distractor-stimulated trials (**Figure 3b**; same procedure as in [6,16,17]). The significance of the amplitude of each frequency component was assessed using a Monte Carlo simulation, under the null hypothesis that the d's of each observer in the target-stimulated and distractor-stimulated conditions were independent of the TMS delay (10,000 iterations). For each iteration, we recomputed the grand-averaged d' difference between the target-stimulated and distractor-stimulated conditions at each delay, and its amplitude spectrum. For each frequency component, we sorted these surrogate data in ascending order and calculated confidence intervals with corresponding *p* values. For the amplitude analysis, we only consider a one-tail statistic because a peak in the amplitude spectrum, if present, can only be positive (we also display the two-tail statistic for additional information). We also computed the average across observers of the phase difference between target-stimulated and distractor-stimulated. We normalized the complex vector to a unit length implying that its phase will always equally contribute to the average, regardless of its amplitude. This normalization allows us to account for situations in which amplitude modulations that would occur independently of phase effects would obscure these effects. The significance of the phase of the 5Hz component was assessed using circular statistics. A parametric two-sample k-test was used to compare the von Mises distributions of the phase for the invalid target-stimulated and invalid distractor-stimulated conditions across observers. A parametric Watson-Williams test was used to compare their circular means.

Supplemental References

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