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Report

The Temporal Interplay between Conscious and Unconscious Perceptual Streams

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Summary

An optimal correspondence of temporal information between the physical world and our perceptual world is important for survival. In the current study, we demonstrate a novel temporal illusion in which the cause of a perceptual event is perceived after the event itself. We used a paradigm referred to as motion-induced blindness (MIB), in which a static visual target presented on a constantly rotating background disappears and reappears from awareness periodically [1–3], with the dynamic characteristics of bistable perception [4]. A sudden stimulus onset (e.g., a flash) presented during a period of perceptual suppression (i.e., during MIB) is known to trigger the almost instantaneous reappearance of the suppressed target [5]. Surprisingly, however, we report here that although the sudden flash is the cause of the static target's reappearance (the corresponding effect), it is systematically perceived as occurring after this reappearance. Further investigation revealed that this illusory temporal reversal is caused by an ∼100 ms advantage for the unconscious representation of the perceptually suppressed target to access consciousness, as compared to the newly presented flash. This new temporal illusion therefore reveals the normally hidden delays in bringing new visual events to awareness.

Results

Experiment 1

Motion-Induced Blindness Session

The occurrence and duration of motion-induced blindness (MIB) were recorded in three separate sessions (pretest, test, and posttest). In the pretest session, participants (n = 7) reported the onset of subjective disappearance and reappearance of a ring target on a trial-by-trial basis with key presses and releases, respectively (for details, see Experimental Procedures). For each participant, we obtained a distribution of MIB durations, ranging from a few hundred milliseconds to several seconds, and we extracted the first quartile of this distribution ($PreQ_{25}$; mean ± standard error of the mean [SEM] = 631 ± 45 ms). In the test session, within each trial we flashed a dot probe (50 ms duration) inside the static ring target after its subjective disappearance at the exact time delay given by the individual $PreQ_{25}$ for the tested subject (Figures 1A–1C). For ∼25% of trials, this probe should thus arrive after the ring has perceptually reappeared. For the remaining 75%, we confirmed that the probe tended to bring about the ring's reappearance within a short delay [5]: compared with the pretest distribution, the test distribution of MIB durations was evidently shortened ($\chi^2(14) = 115.7$, $p < 10^{-6}$; Figure 1C). After each trial, we asked participants whether they had perceived the probe onset (perceptual cause) or the ring reappearance (perceptual effect) first (Figures 1A and 1B). By design, the expected percentage of ring-first responses should have been ∼25%. Strikingly, however, on average participants reported the ring first on 90% (±5% SEM) of trials. Evidently, the perceived temporal sequence of events was the reverse of the expected sequence, so that, in awareness, the perceptual cause (probe onset) lagged behind its effect (ring reappearance). In the posttest session, we verified that the participants' distributions of MIB durations had not changed in any systematic way relative to the pretest ($\chi^2(17) = 4.98$, not significant [NS]), thus ruling out practice as an explanation for the shortened MIB durations in the test session.

What could explain the observed temporal lag? Did we simply overestimate the duration of $PreQ_{25}$ and present the dot probe too late? For example, motor delays between the perceptual disappearance of the ring and its actual report could have contributed to increasing the likelihood of ring-first responses. However, in order to account for 90% ring-first percepts, the extent of that overestimation would have had to be at least 1350 ms (the time difference between $PreQ_{90}$ and $PreQ_{25}$; Figure 1C), a value unlikely to be explained by motor delays.

Control Session

Is this phenomenon specific to perceptually suppressed but physically present stimuli, or would the same effect occur with a ring that physically disappears from the screen? In a control experiment (with a static background that did not induce MIB), we evaluated participants' temporal order judgment between a ring onset and a probe onset in a reappearance session (designed to simulate the experimental sequence of the test session, but with an actual removal of the ring) and an appearance session (serving as a baseline, without any prior exposure to the ring). In both cases, the stimulus onset asynchrony (SOA) between the ring's physical onset and the probe onset (ring-probe SOA) was varied across trials. Psychometric functions for temporal order judgment (see Experimental Procedures) were used to determine the individual point of subjective simultaneity (PSS): the SOA leading to 50% ring-first responses (Figure 1D). The PSS values for each participant (n = 5) were subjected to a t test against 0 ms. The mean PSS (± SEM) was −1.1 ± 4.2 ms for the reappearance session ($t_4 = -0.26$, NS), and 6.5 ± 7.1 ms for the appearance session ($t_4 = 0.91$, NS), which did not differ significantly from 0 ms. The fact that temporal order judgments were accurate in both conditions implies that no significant perceptual processing bias existed between the dot probe and the target ring that could have caused a temporal advantage for the ring. Furthermore, a preview followed by physical disappearance of the ring was not sufficient to induce a temporal reversal. In other words, the temporal illusion obtained in the MIB experiment appears to be a specific property of stimuli that are physically present but temporarily rendered invisible.

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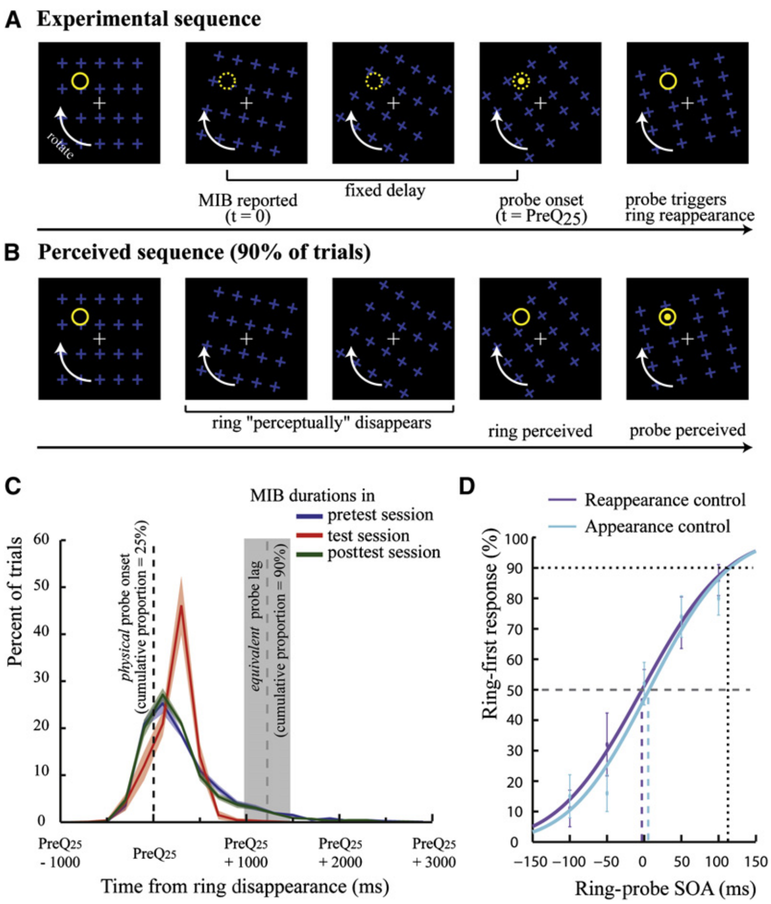

Figure 1. The Illusory Temporal Reversal Phenomenon: Experiment 1

(A) Experimental sequence. Participants performed three sessions. In both the pretest and posttest sessions, they pressed a button when the static ring disappeared from awareness, held the button, and released it when the ring perceptually reappeared. The corresponding first quartile of the distribution of motion-induced blindness (MIB) durations in the pretest session ($PreQ_{25}$) was used as the time delay for probe onset in the test session (illustrated here), where, in addition to the MIB responses, participants indicated whether the ring reappearance or the probe onset was perceived first.

(B) Perceived sequence. Based on the nature of the design, the expected percentage of ring-first responses should have been ~25%. Strikingly, however, an average of 90% ring-first responses was observed. In other words, participants perceived the ring target reappearance before they perceived the flash probe. Note that there need not be a direct temporal correspondence between the individual frames illustrating the experimental (A) and perceived (B) sequences. The basic phenomenon is also demonstrated online at http://www.cerco.ups-tlse.fr/~rufin/illusoryreversaldemo.

(C) Averaged histograms of MIB duration. Here we plot the histogram of MIB durations defined as the time length (ms) between target reappearance and disappearance for the pretest (blue), test (red), and posttest (green) sessions. All participants' MIB duration distributions were first aligned to their corresponding $PreQ_{25}$ before averaging. Confirming results from Kawabe et al. [5], distributions before the probe onset were similar across sessions, but in the test session the probe presentation usually triggered the reappearance of the ring, as indicated by the narrowing of the distribution after probe onset (i.e., $PreQ_{25}$). The gray dotted line indicates the time at which the probe would have needed to be presented, according to the pretest distribution, to account for the observed 90% ring-first percepts (i.e., the 90th percentile of the pretest distribution). Transparent shaded areas represent standard error of the mean (SEM).

(D) Psychometric functions for temporal order judgment in the control sessions. Averaged data from each session in the control experiment were fitted with a cumulative normal distribution. The percentage of ring-first responses is plotted as a function of ring-probe stimulus onset asynchrony (SOA; positive values indicate that the ring reappeared earlier than the probe onset). The purple curve is the result from the reappearance session, in which the ring physically disappeared and reappeared with a delay, mimicking the sequence in the main MIB experiment. The light-blue curve is the result from the appearance session, in which the ring and the probe were simply presented with a variable time SOA (without previous exposure of the ring). No systematic bias in temporal order judgment between probe and ring onsets was observed in either session. Note that, based on the psychometric curves of these two control experiments, the observed 90% ring-first responses in the MIB experiment would correspond to a temporal offset bias of ~110 ms, as indicated by the black dotted line.

Experiment 2

The observed 90% ring-first responses indicate a robust temporal advantage for the reappearance of the perceptually suppressed ring target as compared to the newly presented flash probe. Based on the fitted psychometric function from the control session in experiment 1, 90% ring-first responses could correspond to a temporal offset bias of at least ~110 ms in favor of the ring target (Figure 1D). There are two logical alternatives to account for this temporal advantage: either the flash probe is perceived too late compared to its normal perceptual latency because it is presented during a perceptually suppressed period (the illusion would thus have affected the probe), or the existing unconscious ring representation was perceived with a shortened latency (the illusion would thus have affected the ring target). We tested the first alternative by comparing the perceptual latency of the flash probe to that of another flash probe presented at a different location, outside of MIB. In this experiment, two rings were presented in opposite hemifields on a rotating background, and the observers (n = 4) monitored the two locations while only reporting disappearance of the left ring (MIB). They were instructed to reject any trial in which the right ring had also disappeared, even briefly. At a fixed time (500 ms) after the onset of MIB, a flash probe was presented in each ring, and subjects reported the perceived order of appearance of the two probes. The delay between the onsets of the two probes was adjusted according to a QUEST procedure [6] to determine the PSS. The mean PSS (± SEM) was −9.5 ± 12.0 ms. This was not different from a control condition in which the background did not rotate (so that no MIB could occur), and the same subjects reported a mean PSS of −6.8 ± 9.9 ms between the left and the right flash probes. In summary, the processing of the probe at the MIB location was not delayed compared to its normal perceptual latency; instead, the results support the second of the above-mentioned alternatives, i.e., that the preexisting ring representation in the unconscious stream was reactivated in the conscious stream faster than normal—and faster than it takes a newly presented probe to reach consciousness.

Experiment 3

In order to directly quantify the temporal advantage of the perceptually suppressed ring, we modified the test session from experiment 1 by introducing a nonsalient color change of the ring target (Figures 2A and 2B; see also Experimental Procedures) that occurred at various SOAs relative to the onset of the flash probe (ColorChange-Probe SOA). At the

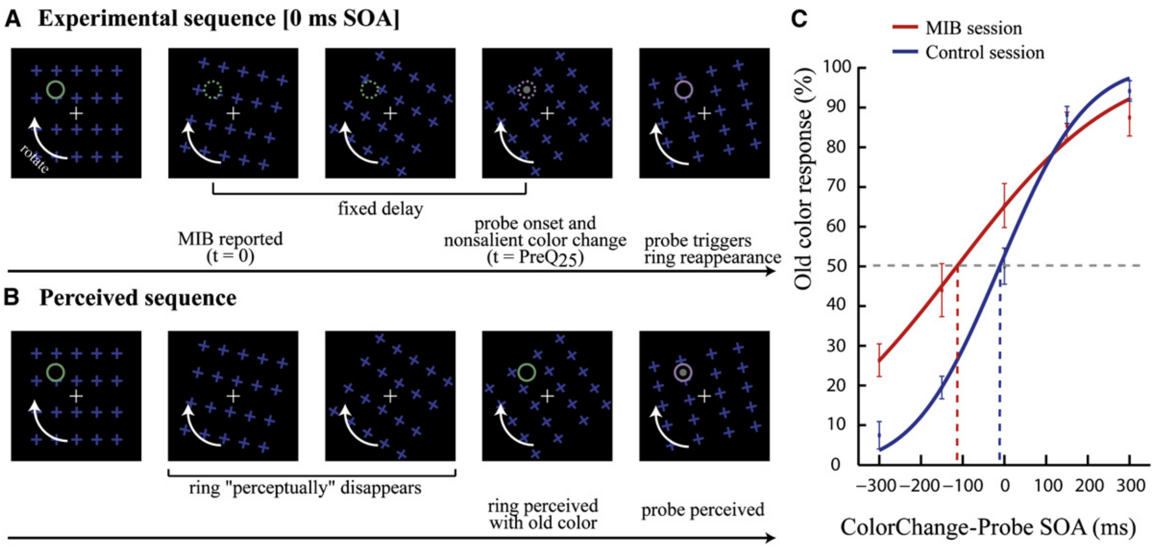

Figure 2. Measuring the Extent of the Temporal Reversal: Experiment 3

(A) Experimental sequence for the 0 ms ColorChange-Probe SOA condition. As in experiment 1, each participant performed a pretest session to determine his or her corresponding $PreQ_{25}$ for the test session. In the test session, a flash probe was again presented at the $PreQ_{25}$ to trigger an early reappearance of the ring target. Furthermore, the color of the ring target was changed with varied SOA relative to the onset of the probe (−300, −150, 0, 150, 300 ms, with negative SOAs referring to color changes that occurred before the probe onset). Here we present the trial sequence for the 0 ms ColorChange-Probe SOA condition. At the end of each trial, participants responded to two questions: first, whether the ring reappearance or the probe onset was perceived first, and second, whether at ring reappearance they perceived the old or the new color first.

(B) Perceived sequence. In a typical trial, participants perceived that the ring target reappearance occurred earlier than the probe onset; furthermore, the ring target reappeared first with the old color and then changed to the new color. Note that the color change per se did not trigger early target reappearance (see Figure S1A for more detailed evidence).

(C) Psychometric functions for color judgment in the MIB and control session in experiment 3. Averaged data of color judgments from the MIB and the control sessions were fitted with a cumulative normal distribution. The percentage of old color responses is plotted as a function of ColorChange-Probe SOA (negative values indicate that the color change occurred earlier than the probe onset). The red curve is the result from the MIB session, in which the ring changed its color with varied SOA relative to the probe onset while participants experienced MIB. The blue curve is the result from the control session, in which the ring changed its color with varied SOA relative to the probe onset without any MIB (i.e., the background was not rotating and the ring was always visible). For the control session, there is no perceptual bias toward either the old or the new color when the color change occurs simultaneously with the probe onset. For the MIB session, however, there appears to be a perceptual bias toward the old color. In other words, the color change would need to have occurred ∼100 ms before the probe onset for participants to show no perceptual bias toward either color.

end of each trial, participants (n = 10) responded to two questions: first, whether the ring reappearance or the probe onset was perceived first, as in experiment 1 (on average, participants made 76% ± 5% ring-first responses, a value which qualitatively replicated the illusory temporal reversal observed in experiment 1), and second, what color the ring was when it first reappeared (old or new color). By plotting the color choice probability (i.e., old or new) as a function of ColorChange-Probe SOA, we could determine the moment at which the unconscious ring representation was updated into awareness. All participants also performed a similar color judgment (serving as a baseline) in a control session in which no MIB was induced (i.e., the background was not rotating), and the participants reported the perceived color of the ring at the time of the flash probe onset.

Figure 2C illustrates the psychometric curves for the color judgment as a function of ColorChange-Probe SOAs for the MIB session and the control session. Although in the control session, there was no color perception bias (50% ± 5% SEM) at 0 ms SOA, during the MIB session, participants were biased toward reporting the old color on 65% of trials on average (±6% SEM). Again, we obtained individual PSSs (the SOA leading to 50% old-color responses) that were used to quantify the temporal delay responsible for the observed color perception bias. The mean PSS (± SEM) for the MIB session (−122 ± 29 ms) was significantly different from the mean PSS for the control session (−14 ± 14 ms, $t_9 = 3.37$, $p < 0.005$, one-tail). Thus, the color change would need to have occurred on average 108 ms before the probe onset for participants to perceive the two events as simultaneous. In other words, after the flash probe triggered the ring reappearance, the first ring color that participants tended to perceive was the color of the ring as it had been ∼100 ms before the flash probe onset. Most importantly, the magnitude of this temporal delay fits well with the finding from experiment 1 of a temporal advantage of at least 110 ms for the perceptually suppressed ring target as compared to the new probe.

We also verified that, as in experiment 1, the probe tended to bring about the ring's reappearance [5] (see Figure S1B available online); in contrast, the nonsalient color change by itself had no effect on the ongoing MIB (Figure S1A).

Experiment 4

Does the temporal illusion depend on the mismatch between the perceptual time courses of two distinct objects (the "old" ring and the "new" probe), or could it also be obtained for a single object as a result of the temporal mismatch between its representations at the conscious and unconscious levels? To address this, we modified the test session from experiment 3 by introducing a salient color change of the ring target to trigger the early reappearance of the target without the need for a flash probe (Figure 3; see also Experimental Procedures).

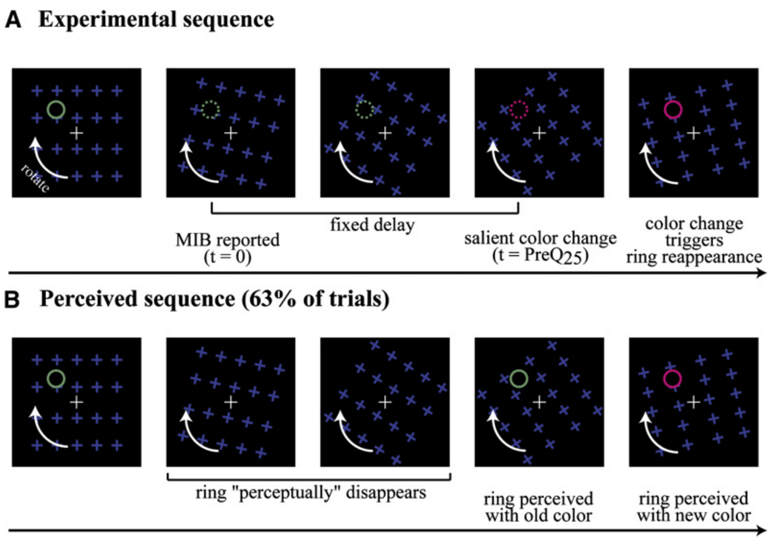

Figure 3. Color Change Acting as the Probe Event: Experiment 4

(A) Experimental sequence. Again, each participant performed a pretest session to determine his or her corresponding $PreQ_{25}$ for the test session. In the test session, instead of a probe, we changed the ring target to another salient color at the corresponding $PreQ_{25}$ to trigger an early reappearance of the ring target. At the end of each trial, participants responded to a single question: whether, at ring reappearance, they perceived the old or the new color first.

(B) Perceived sequence. On average, for 63% of trials, participants perceived the old color first when the ring target reappeared from MIB.

In other words, there was no "new object" in this paradigm, but rather only old versus novel features of a preexisting object. As before, the salient color change occurred at the corresponding $PreQ_{25}$ determined by each participant's pretest session. At the end of each trial, participants (n = 6) reported which color (old or new) they had first perceived when the ring target reappeared from MIB; by design, one would thus expect ~25% of old-color responses.

As in experiments 1 and 3, the probe event (here, the color change) triggered the reappearance of the target (Figure S2). Furthermore, when the target reappeared from MIB, it was first perceived by the participants with its old color in 63% ± 6% of trials on average, instead of the expected ~25%. This result is remarkable, because in most trials it was the switch to the new color that triggered the perceptual reappearance of the ring; that is, the new color of the ring must have first been registered by the visual system at the unconscious level, which resulted in the conscious reappearance of a ring clad in its old color.

Experiment 5

To generalize our conclusions to other types of perceptual suppression, we also tested the phenomenon during binocular rivalry. Following the same logic as during the MIB experiment, we presented a probe to trigger an early switch of dominant percepts between two eyes. In this case, the illusory temporal reversal (i.e., perceiving the switch before perceiving the probe) was present, but with a reduced magnitude (for details, see Figure S3), suggesting that the level of perceptual suppression may be different from that of MIB.

Discussion

In the current study, we present converging evidence for a novel temporal illusion: a visual stimulus (e.g., a ring) temporarily outside the realm of consciousness (i.e., during MIB) can be perceived to reappear before the event (e.g., a flash) that triggers its reappearance, leading to an illusory temporal reversal of cause and effect. Our results further suggest that this illusory temporal reversal is caused by an ~100 ms temporal advantage for updating the conscious representation from the preexisting unconscious representation of the perceptually suppressed static target, as compared to the newly presented sudden flash. This illusion adds to a number of previous reports in which the temporal order between events in the real world was shown to disagree with the corresponding perceived order [7–16].

In our case, the fact that illusory reversals only occur after one of the two stimuli has been perceptually suppressed has strong implications for the mechanisms of conscious perception in the brain. We reported a temporal advantage of ~100 ms for updating a preexisting unconscious representation to conscious awareness, as compared to consciously perceiving an entirely new stimulus (experiments 1–3) or a new feature of the existing stimulus (experiment 4). This temporal advantage suggests that there normally exists an integration period of at least 100 ms before new stimuli can enter consciousness. Although this integration period is consistent with a purely feed-forward model of conscious vision, another class of theories that could explain the phenomenon invokes feedback or reentry of neural signals after the first feed-forward sweep for a stimulus to be consciously perceived [17, 18]. Accordingly, MIB or rivalry suppression would block reentry signals and thus prevent awareness. In this view, feed-forward processing of the probe would trigger the reentry of the preexisting representation of the target, which is temporally blocked from being consciously perceived, while the compulsory reentry of the probe (and/or of the color change) would delay its perceptual awareness, resulting in an illusory reversal. Even though this theory is clearly not the only possible way of explaining our results, the observed ~100 ms temporal advantage in our data fits well with the suggestion that the key recurrent processing for conscious perception occurs in ~100 ms [18, 19].

In any case, the novel illusory phenomenon reported here suggests that on the way to consciousness, "out of sight" can lag "out of mind" by at least ~100 ms.

Experimental Procedures

Information in this section is in summarized form. For more details, see Supplemental Experimental Procedures.

Experiment 1

Motion-Induced Blindness Session

The display (classic MIB) is illustrated in Figure 1A. In the pretest session, participants reported the disappearance and reappearance of the ring trial-by-trial. Accordingly, we obtained a distribution of MIB durations and extracted its first quartile ($PreQ_{25}$) for each participant. In the test session, we flashed a dot probe (50 ms duration) at the location of the ring at the exact time delay of this first quartile ($PreQ_{25}$) after the reported onset of MIB. In addition to reporting the occurrence of MIB as previously, at the end of each trial participants were also required to judge the perceived temporal order between the flashed probe and the ring. Finally, a posttest session (same as the pretest session) ensured that the distribution of reported MIB durations had remained relatively stable from session to session.

Control Session

We simulated the experimental sequence of the MIB session with a static background (i.e., no MIB; the ring physically disappeared and reappeared, or simply appeared at a given time). Participants judged the temporal order between the ring appearance/reappearance and the probe onset. Critically, we varied the stimulus onset asynchrony (SOA) between the ring appearance/reappearance and the probe and determined the point of subjective simultaneity (PSS) under these control conditions.

Experiment 2

There were two sessions: an MIB session and a control session. In both sessions, two static ring targets were displayed, one in the upper left visual field and one in the upper right visual field. In the MIB session, participants monitored the two locations but only reported the disappearance and reappearance of the left target (trials were rejected when the right target underwent MIB). At a fixed delay (500 ms) after reported disappearance of the left ring, a flash probe was presented within each ring with a variable SOA between the two flash probes. To ensure that the left ring target was still under the influence of MIB at the corresponding flash probe onset, we only considered trials in which the reported MIB duration exceeded 600 ms. At the end of each trial, participants judged the temporal order between the left and right flash probes. The SOA was adjusted online with an adaptive staircase procedure (QUEST [6]). In the control session, the procedure was the same but with a static background (i.e., no MIB).

Experiment 3

Motion-Induced Blindness Session

The display is illustrated in Figure 2A. All procedures were similar to experiment 1. However, in the test session, the color of the ring target was changed from dark green to dark purple (the color used in the pretest session) with varied SOAs relative to the probe onset (ColorChange-Probe SOA: −300, −150, 0, 150, 300 ms). For each trial, participants reported (1) whether the ring reappearance or the probe onset was perceived first and (2), when the ring reappeared, which color they perceived first (old or new color).

Control Session

The control session was similar to the test session except that no MIB was induced (i.e., the background was not rotating).

Experiment 4

The procedures were similar to experiment 1 except that a salient color change of the ring (from dark green to bright purple) played the role of the flash probe. For each trial in the test session, participants reported the color they perceived first when the ring reappeared (i.e., old or new color).

Experiment 5

We applied the same logic as in experiment 1 to a different perceptual suppression paradigm: binocular rivalry. In this case, an early dominant percept switch (just like the ring reappearance in experiments 1–4) between the two eyes was triggered by the flash probe; subjects reported the perceived temporal order between the dominant percept switch and the flash probe.

Supplemental Data

Supplemental data include Supplemental Experimental Procedures and three figures and can be found online at http://www.cell.com/current-biology/supplemental/S0960-9822(09)01836-3.

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