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The Motion-Silencing Illusion Depends on Object-Centered Representation

Qihan Wu and Jonathan I. Flombaum
Department of Psychological and Brain Sciences, Johns Hopkins University

Abstract

Motion silencing is a striking and unexplained visual illusion wherein changes that are otherwise salient become difficult to perceive when the changing elements also move. We develop a new method for quantifying illusion strength (Experiments 1a and 1b), and we demonstrate a privileged role for rotational motion on illusion strength compared with highly controlled stimuli that lack rotation (Experiments 2a to 3b). These contrasts make it difficult to explain the illusion in terms of lower-level detection limits. Instead, we explain the illusion as a failure to attribute changes to locations. Rotation exacerbates the illusion because its perception relies upon structured object representations. This aggravates the difficulty of attributing changes by demanding that locations are referenced relative to both an object-internal frame and an external frame. Two final experiments (4a and 4b) add support to this account by employing a synchronously rotating external frame of reference that diminishes otherwise strong motion silencing. All participants were Johns Hopkins University undergraduates.

Keywords

vision, object perception, change detection, illusions, preregistered

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Motion silencing (MS) is a striking illusion wherein changes that are otherwise salient become difficult to perceive when the changing elements move (Suchow & Alvarez, 2011). The typical stimulus includes 100 dots arranged to form a ring. Each dot starts with a random color, changing color by continuously cycling through color space. The changing colors are highly noticeable when the ring is stationary but barely so when the ring rotates. Now the color changes become difficult to detect, silenced, an illusion that gains strength as rotation speed increases.

The prevailing explanation for the illusion appears to be that local change detectors have small receptive fields (Suchow & Alvarez, 2011). Fast rotation means that color changes happen too slowly to register. Effectively, if an item remains unchanged as it passes through a detector, the change cannot be caught, even if the item has changed quite a bit when you compare it after and before.

The present study sought to explore MS in two ways. First, we sought to investigate the effects of silencing on objective discrimination. A changing but silenced stimulus should be difficult to distinguish from an unchanging stimulus. Second, we sought evidence to support a higher-level explanation for the illusion: that it arises when color changes are detected but difficult to attribute to specific locations. Toward this end, we examine whether rotation amplifies silencing, compared with similar but nonrotational motion. We reason that rotation complicates the process of attributing changes to locations because it increases the demand for labeling locations in multiple reference frames at once.

We were motivated to explore whether rotation increases silencing for two related reasons. First, we observed that nearly all the examples of silencing involve rotation. But the two exceptions we are aware of support the view that silencing is an attribution error. Peirce (2013) demonstrated that motion itself can be silenced in the presence of global changes—such as

Corresponding Author:
Jonathan I. Flombaum, Department of Psychological and Brain Sciences, Johns Hopkins University
Email: flombaum@jhu.edu

simultaneous and directional luminace changes to a group of dots—a result that is not consistent with motion speed as the culprit. Poljac et al. (2012) found more silencing for dots arranged in the form of a person compared with the same figure upside down. They suggest that the upright person draws on an organized representation that complicates attribution of change by demanding that each dot be thought of in terms of its relation to the external world and also in terms of its relation to the person as a whole. On this basis we theorized that if rotation draws on more organized (or good Gestalt) representations than other kinds of motion, then it should show stronger silencing.

Our second motivation follows from studies of individuals with unusual object perception deficits: one individual called AH (McCloskey et al., 1995) and another with the pseudonym Davida (Vannuscorps et al., 2022). Although their cases diverge in certain ways, both individuals misperceive and misremember the orientations of elongated objects, making errors that are limited to certain kinds of reflections (Vannuscorps et al., 2022). This has been cited as evidence of object representations that are built through a structured process that first extracts a bounded object from retinal input, then describes it within its own object-centered frame of reference, and then locates the object in space relative to an external frame of reference by storing information that marks the current alignment between external and object-centered frames. The specificity of the neuropsychological deficits is explained as a symptom of lost information about the relationship between the external and internal reference frames.

We reasoned that like an elongated object with clear axes, a rotating ring is perceived as a coherent object, or at least as a highly organized structure, and that perceiving its rotation is straightforwardly the perception of continuous change between the present alignment of external and object-centered reference frames. More specifically, the positions of the 100 elements in an MS stimulus are represented in at least two ways simultaneously: by reference to perpendicular axes that bisect the ring and by reference to fixed, external axes, such as a display. In rotational motion, element positions change when referenced externally but not when referenced internally.

Our proposal is that MS is caused by the challenge of attributing changes to their respective locations, owing to the large number of simultaneously changing and moving elements. Rotation exacerbates the challenge by causing disagreement between external and internal reference regarding location changes. This leads to further uncertainty about how to attribute detected changes, what is perceived as silencing. The main objective of the reported experiments is therefore to address a first-principles question about the perception of rotation: How do we perceive the rotation of a whole object from an assembly of local motion signals? The answer we provide is that whole-object representations take precedence, providing a scaffolding for the description of local signals with reference to object-defined frames and then locating the whole object and its changing orientation with external reference.

To pursue this path requires a method that would show the presence of MS through a consequence on behavior. Further, we sought a method in which responses could be objectively identified as right or wrong and where latency to respond could be the vehicle for comparison across conditions, a proxy for the perceived similarity between two stimuli. We therefore implement a two-alternative forced-choice task. A rotating unchanging ring should be a good distractor, slowing latency to response, when a person searches for a rotating and changing ring; but an unchanging ring should not be a good distractor during search for a changing one if both rings remain stationary. Experiment 1 directly tests this prediction while also replicating a known effect of speed on the strength of the illusion. Experiments 2 and 3 apply these methods to contrast rotational and nonrotational motion. Experiment 4 investigates a case of rotation that obviates the need to update the relation between the internal reference and external reference, comparing it with a case that does not.

Statement of Relevance

Rotation is pervasive: Things spin and twirl and orbit. We investigate a computational challenge specific to the perception of rotation: tracking how rotating parts stay stationary in relation to one another while they change their positions relative to the external world. Think of a Ferris wheel. The cars remain in stable relative positions even as they move relative to an observer. To investigate the perception of rotation, we employ motion silencing, a striking and illusory failure to perceive change. We show that rotation has a privileged effect on illusion strength because it involves simultaneous tracking within internal and external reference frames. The challenge of simultaneous reference has been cited to explain deficits for the perception of object orientation in single-patient studies. The eight experiments reported here sum to explain motion silencing similarly, and they suggest a functional role for object-centered frames of reference in the perception of rotational motion.

Experiments 1a and 1b

The purpose of these experiments was to demonstrate that MS feeds into later processing, such that a silenced stimulus is observably hard to distinguish from an unchanging stimulus. We meet this goal by asking participants to identify which of two stimuli undergoes continuous changes (color in Experiment 1a, size in Experiment 1b).

Experiment 1a

Method.

Experiment link. Experiment 1a can be viewed online with a web browser at https://www.qw.perceptionresearch.org/motion_silencing_exp_demo/motion_silencing_exp_1_demo.html.

Participants. We aimed to collect data from 30 participants. The sample size was determined on the basis of pilot experiments conducted prior to preregistration. Any participant with a correct response rate below 75% overall was excluded and replaced. Such data were discarded automatically and never viewed. We tested a total of 30 undergraduates for Experiment 1a.

Participants were recruited through an online system for students to enroll in studies and receive course-related credit. Demographic information was not collected because it is not related to the hypothesis of the current study. Participants completed the experiment on a personal device. The instructions and sign-up page asked that they use a laptop or desktop computer, not a mobile device. All reported experiments were approved by the Johns Hopkins University Homewood Institutional Review Board.

Stimuli and procedures. In this and all subsequent experiments, parameters are reported in pixels because the experiments were run online. Each trial included two boxes, and each box included a ring comprising 100 randomly colored dots. Each box was 410 pixels by 410 pixels. The boxes were separated from each other by 200 pixels between their left and right edges. They were centered in the display vertically. The RGB values for the boxes were rgb(169,169,169), and the RGB values for the webpage background were rgb(128,128,128). The inner radius of each ring was 50 pixels, and the outer radius was 100 pixels. Each individual dot was 12.5 pixels in radius. A black fixation square (10 pixels) was placed in the middle of the screen, between the two boxes that contained the rings. Instructions included the request that participants fixate the center of the display during the times between trials, prior to the onset of stimuli.

Immediately upon the start of a trial, both rings either rotated clockwise and did so continuously through the trial (the rotation condition) or were stationary and remained so throughout the trial (the stationary condition). In the rotation trials, the two rings rotated at the same clockwise speed. Across trials, there were three rotation speeds, 75°/s, 105°/s, and 135°/s, with 60 trials of each. The stationary condition can be thought of as a 0°/s condition, and there were also 60 such trials in Experiment 1a. Therefore, Experiment 1a included a total of 240 (randomly distributed and counterbalanced) trials per participant.

During a trial, the dots within one and only one ring changed color continuously at a rate of 211.76°/s along the hue axis in HSV (hue, saturation, value) color space. Each dot was initialized with a random hue, which was uniformly sampled from the hue axis. The saturation and value axes were fixed at 100%.

The task for a participant was to identify, as quickly as possible, which of the two rings included the dots that were changing color. A key press was used to indicate the box (labeled 1 or 2). Stimuli remained present on screen until a key press. Latency to respond was recorded as well as accuracy. Latency to respond was analyzed only in trials with correct responses. The same criterion applied to all experiments reported here. After a participant made a response, the stimuli disappeared, replaced by instructions that invited the participant to move to the next trial by clicking the Next button.

Reaction time and accuracy validation. Results were computed while excluding any individual trial with a reaction time less 200 ms or greater than 2,000 ms. Two hundred milliseconds is a typical cutoff time, close to the time required merely to execute a key press. Trials of 2,000 ms were excluded because of pilot experiments prior to preregistration, which suggested that some subjects might step away from the task for long durations, a challenge of online experiments. We analyzed results only from trials with correct responses. These criteria allowed us to analyze results from 7,024 trials in Experiment 1a. The same criteria are applied to all subsequent experiments.

Results. We predicted that MS should cause a moving and changing stimulus to look similar to a moving and unchanging one. But when the rings do not move, we predicted, a changing stimulus should be quick to detect. Response latencies (Experiment 1a) as a function of motion speeds are plotted in Figure 1, which also contains a still frame from Experiment 1a. A linear regression indicated a significant and positive effect of motion speed on response time, $r^2 = .27$, $F(3, 116) = 14.16$, $p < .001$. The graded effect of motion speed on latency shows the

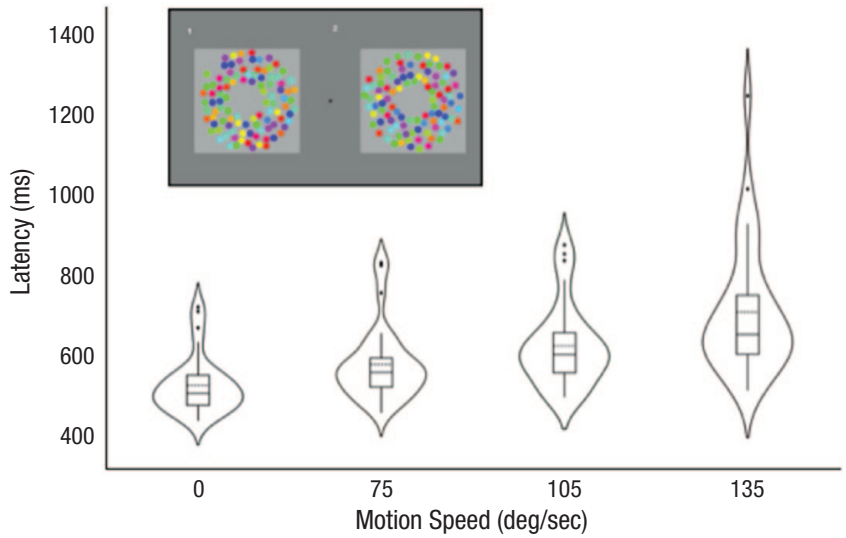


Fig. 1. A still sample frame (inset) from Experiment 1a. In one-quarter of trials, the two rings were stationary and dots changed color in only one of them. In the remaining three-quarters of trials, the two rings rotated clockwise at one of three speeds. The task was always to indicate by key press which of the two rings changed color. Results are shown as violin plots for response latency against motion speed (where 0 is the stationary condition). Solid lines and dashed lines in the boxes indicate medians and means, respectively. Experiment 1a can be viewed online with a web browser at https://www.qw.perceptionresearch.org/motion_silencing_exp_demo/motion_silencing_exp_1_demo.html.

promise of these methods as a means to compare conditions in terms of degree of motion silencing.

Experiment 1b

Method. The details of Experiment 1b were identical to Experiment 1a, except as noted.

Experiment link. Experiment 1b can be viewed online with a web browser at https://www.qw.perceptionresearch.org/Color_motion_perception_30/motionSilence_exp_30.html.

Participants. We tested a new group of 31 undergraduates until we obtained data from 30 participants who met our inclusion criteria. The recruitment and instruction details were the same as Experiment 1a.

Stimuli and procedures. The details of Experiment 1b were identical to Experiment 1a, except as noted. Each trial included two boxes, and each box included a ring comprising 100 gray dots. The RGB values for the dots were rgb(105,105,105), and the dots did not change color. When the rings in a trial rotated, they did so at speed of 90°/s (the rotation condition). Otherwise, the rings remained stationary (the stationary condition). There were 60 trials of each condition in Experiment 1b. Therefore, Experiment 1b included a total of 120 (randomly distributed and counterbalanced) trials per participant.

During a trial, the dots within only one ring changed size continuously, getting either larger or smaller at a rate of 30 pixels per second. Each dot was initialized with a size randomly chosen between 4.5 and 12.5 pixels in radius and with a randomly selected change direction. When a dot hit a boundary size, it reversed its change direction. The task was to identify the ring with the size-changing dots.

Reaction time and accuracy validation. We analyzed 3,503 trials with correct responses and response latencies between 200 ms and 2,000 ms.

Results. Experiment 1b included only a stationary and a rotating condition (without a speed manipulation). A planned one-tailed t test showed a significant difference on latency for the rotating compared with the stationary condition, $t(29) = 9.48$ $p < .001$, $M = 162.44$, $d = 1.73$. Figure 2 shows the results along with a still of the stimulus.

Experiments 2a and 2b

The traditional ring stimulus for MS admits to interpretation as either rotation or element motion. By "rotation," we mean that the ring is a single object, with rotation driven by one source of kinetic energy. By "element," we mean that each of the dots moves on its own, with its own source of kinetic energy. (By analogy, picture a rotating record with speckles on it versus individual

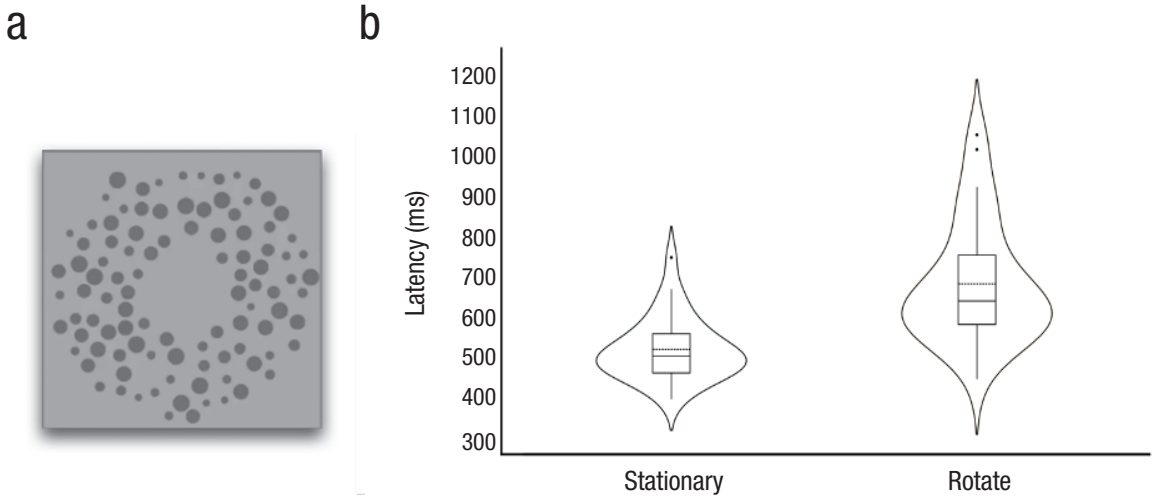


Fig. 2. (a) A still sample frame from Experiment 1b. In half of trials, the two rings were stationary and dots changed size in only one of them. In the remaining half of trials, the two rings rotated clockwise. The task was always to indicate by key press which of the two rings included dots that changed in size. Results are shown as (b) violin plots for response latency against motion type. Solid lines and dashed lines in the boxes indicate medians and means, respectively. Experiment 1b can be viewed online with a web browser at https://www.qw.perceptionresearch.org/Color_motion_perception_30/motionSilence_exp_30.html.

dancers moving around a circle, respectively.) In Experiment 2, we employ a stimulus without the property of dual interpretation. A square allows for disentangling whole-object rotation and element motion. In some trials, we rotate the square around its own center—a rotation condition not dissimilar in appearance from the ring in Experiment 1—while in other trials, the dots translated about the square's perimeter, producing an impression more consistent with element motion.

Experiment 2a

Method.

Experiment link. Experiment 2a can be viewed online with a web browser at https://www.qw.perceptionresearch.org/motion_silencing_exp_demo/motion_silencing_exp_2_demo.html.

Participants. We tested a new group of 30 undergraduates.

Stimuli and procedures. The stimuli in Experiment 2a differed from those in Experiment 1a in only one important way: The 100 dots in each box did not make up a ring. Instead, the dots were arranged in a hollow square. There were three conditions in Experiment 2a: In one, the dots translated around the square, as if they were walking the perimeter. In the second condition, the hollow square made up of 100 dots rotated around its own center. And we also included a stationary condition, in which the dots did not move. As in Experiment 1a, the squares in each trial participated in the same motion condition, and only one square included dots that changed color.

The squares were 450 pixels by 450 pixels, and each band was 100 pixels wide. The squares were separated from each other by 200 pixels between their left and right edges. In Experiment 2a, the squares were presented on a background rgb(128,128,128) without a surrounding box.

The rotation speed in the rotating condition was 90°/s. In the translating condition, the dots walked at a speed of 3.24 pixels per second. Each condition was repeated 60 times, so that Experiment 2a included a total of 180 (randomly distributed and counterbalanced) trials per participant.

Reaction time and accuracy validation. We analyzed 5,290 trials with correct responses and response latencies between 200 ms and 2,000 ms.

Results. If rotation potentiates silencing, then a rotating square should silence change, while translating dots should produce less or no silencing. Average response latencies as a function of motion type for Experiment 2a are plotted in Figure 3. A repeated-measures analysis of variance revealed a main effect of motion type on latency, $F(2, 87) = 25.77$, $p < .001$, $\eta^2 = 0.37$. Planned one-tailed paired t tests were used to investigate the results further, revealing that latencies in the rotating condition were significantly longer than in the translating square condition, $t(29) = 6.17$, $p < .001$, $M = 46.03$, $d = 1.13$; that latencies

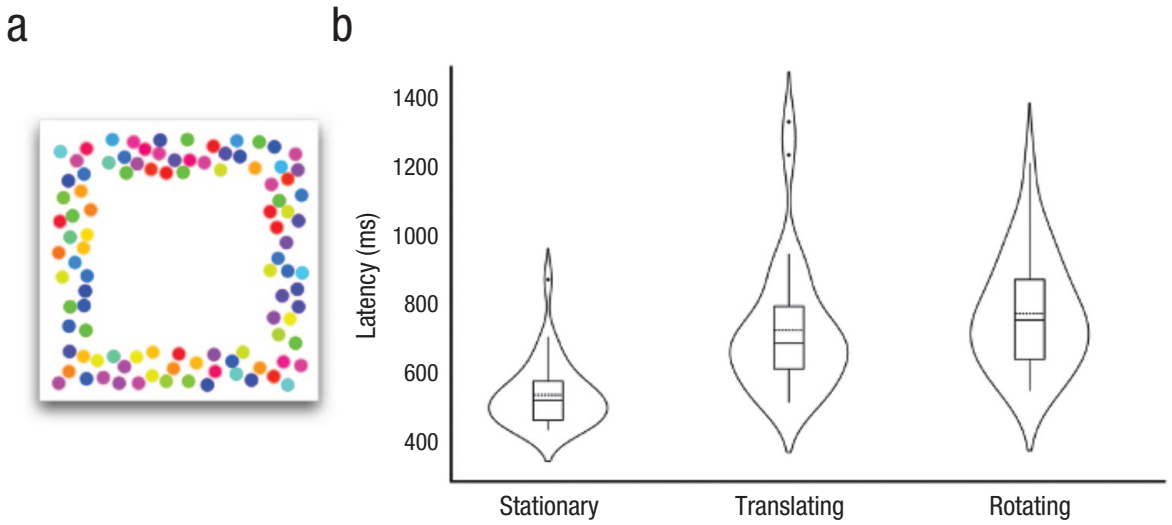


Fig. 3. (a) The stimulus used in Experiment 2a. In one-third of trials, the two squares were stationary and dots changed color in only one of them. In the remaining two-thirds of trials, the dots translated around the perimeters of their respective squares, or the squares rotated clockwise around their respective centers. The task was always to indicate by key press which of the two squares changed color. Results are shown as (b) violin plots for latency against motion type. Solid lines and dashed lines in the boxes indicate medians and means, respectively. Experiment 2a can be viewed online with a web browser at https://www.qw.perceptionresearch.org/motion_silencing_exp_demo/motion_silencing_exp_2_demo.html.

in the rotating condition were significantly longer than in the stationary condition, $t(29) = 11.75$, $p < .001$, $M = 238.027$, $d = 2.15$; and that latencies in the translating condition were longer than in the stationary condition, $t(29) = 9.08$, $p < .001$, $M = 174.52$, $d = 1.66$.

Experiment 2b

Method. The details of Experiment 2b were identical to Experiment 2a, except as noted.

Experiment link. Experiment 2b can be viewed online with a web browser at https://www.qw.perceptionresearch.org/Color_motion_perception_31/motionSilence_exp_31.html.

Participants. We tested a new group of 32 undergraduates until we obtained data from 30 participants who met our inclusion criteria.

Stimuli and procedures. The stimuli in Experiment 2b differed from those in Experiment 2a in only one way: In each trial, the RGB values for each of the 100 dots was set to rgb(105,105,105). During a trial, the dots within only one ring changed size continuously at a rate of 30 pixels per second. Each dot was initialized with a size randomly chosen between 4.5 and 12.5 pixels. The same three conditions were tested in Experiment 2b as in Experiment 2a.

Reaction time and accuracy validation. We analyzed 5,128 trials with correct responses and response latencies between 200 ms and 2,000 ms.

Results. Results of Experiment 2b were similar to 2a, shown in Figure 4. A repeated-measures analysis of variance revealed a main effect of motion type on latency, $F(2, 87) = 28.02$, $p < .001$, $\eta^2 = 0.39$. Planned one-tailed paired t tests showed that latencies in the rotating condition were significantly longer than in the translating square condition, $t(29) = 4.63$, $p < .001$, $M = 51.45$, $d = 0.85$; that latencies in the rotating condition were significantly longer than in the stationary condition, $t(29) = 13.82$, $p < .001$, $M = 233.20$, $d = 2.52$; and that latencies in the translating condition were longer than in the stationary condition, $t(29) = 10.83$, $p < .001$, $M = 214.46$, $d = 1.98$.

Experiments 3a and 3b

In Experiment 3 we employ a structure-from-motion rotating cylinder (Andersen & Bradley, 1998). When there is a column of individual dots and half the dots translate in one horizontal direction while the other half translate in the opposite direction, the impression produced is a rotating cylinder. Rotation here is entirely perceived; none of the individual elements possess angular velocity. Does perceived rotation produce silencing despite the absence of angular motion in practice? As a comparison, the cylinder has a natural baseline: a column where all the dots translate in the same direction. This stimulus includes equal linear motion to the rotating cylinder but no angular motion, in practice or perceived.

Experiment 3a

Method. Details of Experiment 3a were identical to Experiments 1a and 2a, except as described.

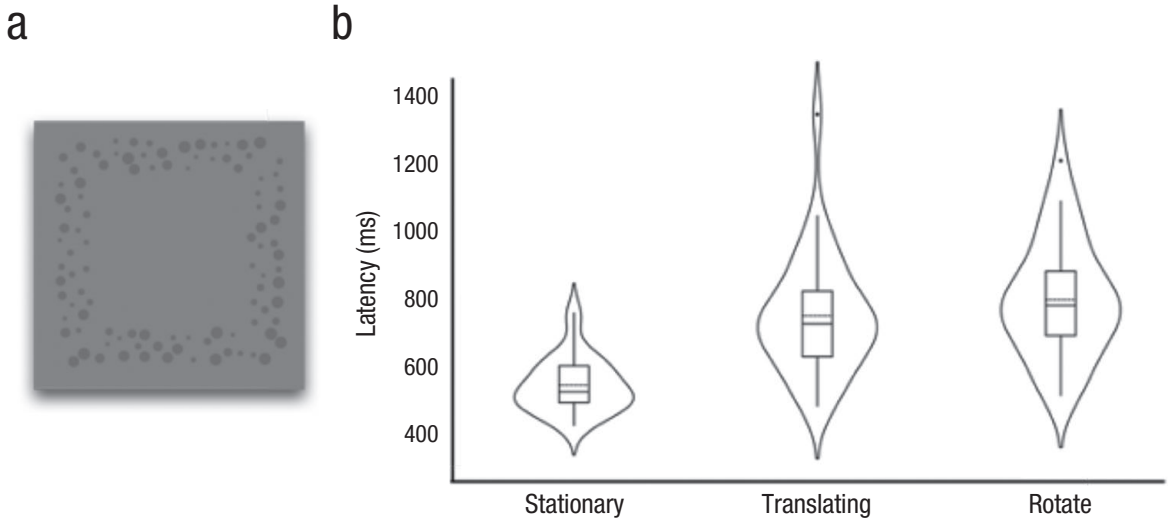


Fig. 4. (a) A still sample stimulus from Experiment 2b. In one-third of trials, the two squares were stationary. In the remaining two-thirds of trials, the dots translated around the perimeters of their respective squares, or the squares rotated clockwise around their respective centers. The task was always to indicate by key press which of the two squares included dots that were changing in size. Results are shown as (b) violin plots for latency against motion type. Solid lines and dashed lines indicate medians and means, respectively. Experiment 2b can be viewed online with a web browser at https://www.qw.perceptionresearch.org/Color_motion_perception_31/motionSilence_exp_31.html.

Experiment link. Experiment 3a can be viewed online with a web browser at https://www.qw.perceptionresearch.org/motion_silencing_exp_demo/motion_silencing_exp_3_demo.html.

Participants. A new group of 31 participants was tested. The increase of one extra subject was unplanned, caused by a subject who signed up for the experiment, neglected to complete it, and then requested to be able to complete it in order to receive the attendant course credit.

Stimuli and procedures. The 100 dots were arranged in a column that was 275 pixels wide by 475 pixels high. The columns were separated from each other by 200 pixels between their left and right edges, and they were centered in the display vertically.

Three conditions were tested in Experiment 3a. One was the stationary condition, where the dots in the column did not move. In the second condition, all the dots translated in the same direction horizontally (translating). In the third condition, half of the 100 dots translated to the left while the other half translated to the right. We call the last condition rotating because it produces a percept of a rotating cylinder (Andersen & Bradley, 1998). The linear motion speed in the translating and rotating conditions was 60 pixels per second, and zero, of course, in the stationary condition. Each condition was repeated 60 times so that the experiment included a total of 180 (randomly distributed and counterbalanced) trials per participant.

Reaction time and accuracy validation. We analyzed 5,421 trials with correct responses and response latencies between 200 ms and 2,000 ms.

Results. We predicted that cylinder rotation should produce silencing, while translation should produce less or no silencing. Average response latencies as a function of motion type for Experiment 3a are plotted in Figure 5b. A repeated-measures analysis of variance revealed a main effect of motion type on latency, $F(2, 90) = 3.78$, $p = .0264$, $\eta^2 = 0.0776$. Planned one-tailed paired t tests showed that latencies in the rotating condition were significantly longer than in the translating condition, $t(30) = 5.92$, $p < .001$, $M = 74.02$, $d = 1.06$; latencies in the rotating condition were also significantly longer than in the stationary condition, $t(30) = 5.10$, $p < .001$, $M = 85.05$, $d = 0.91$; and latencies in the translating condition were not significantly different from those in the stationary condition, $t(30) = 1.26$, $p = .11$, $M = 11.03$, $d = 0.23$.

Experiment 3b

Method. Details of Experiment 3b were identical to Experiment 3a, except as described.

Experiment link. Experiment 3b can be viewed online with a web browser at: https://www.qw.perceptionresearch.org/Color_motion_perception_33/motionSilence_exp_33.html

Participants. A new group of 30 participants was tested.

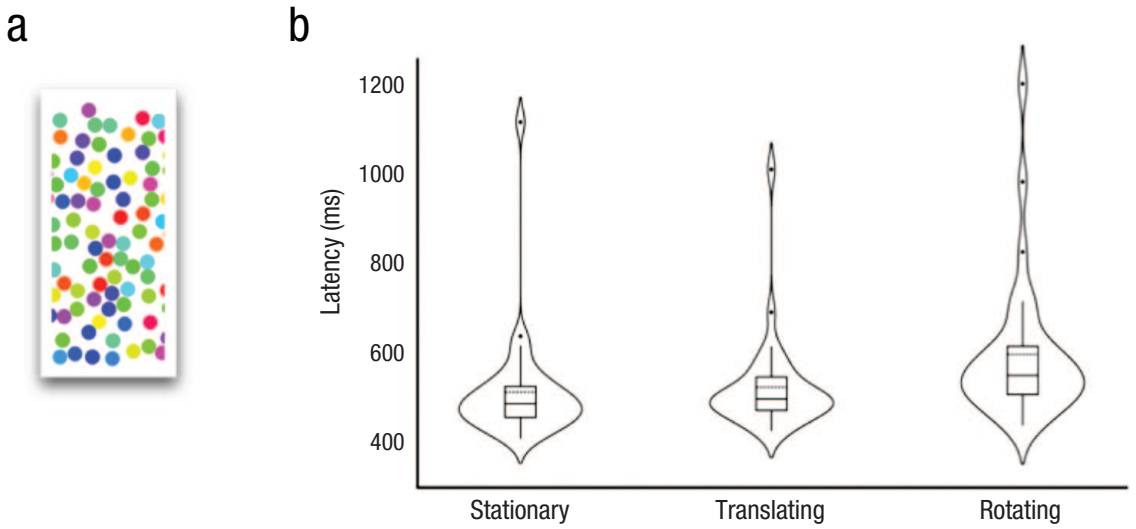


Fig. 5. (a) A still of the stimuli used in Experiment 3a. In each trial, two such columns of dots were presented and the dots in only one of them changed colors continuously. In one-third of trials, all the dots in both columns were stationary (stationary condition). In another one-third of trials, the dots in each column translated in one horizontal direction (translating). In the remaining one-third trials, 50% of dots in each column translated to the left and 50% translated to the right (rotating), which produced a rotating cylinder percept. The task was identical to previous experiments. Results are shown as (b) violin plots for latency against motion type. Solid lines and dashed lines indicate medians and means, respectively. Experiment 3a can be viewed online with a web browser at https://www.qw.perceptionresearch.org/motion_silencing_exp_demo/motion_silencing_exp_3_demo.html.

Stimuli and procedures. The stimuli in Experiment 3b differed from those in Experiment 3a minimally. In each trial, the RGB values for all the 100 dots were set to rgb(5, 200,133). During a trial, the dots within one and only one column changed size continuously at a rate of 30 pixels per second. Each dot was initialized with a size randomly chosen between 4.5 and 12.5 pixels. The same three conditions were tested in Experiment 3b as in Experiment 3a.

Reaction time and accuracy validation. We analyzed 10,487 trials with correct responses and response latencies between 200 ms and 2,000 ms.

Results. Average response latencies as a function of motion type for Experiment 3b are plotted in Figure 6b. A repeated-measures analysis of variance revealed a main effect of motion type on latency, $F(2, 87) = 17.93$, $p < .001$, $\eta^2 = 0.2919$. Planned one-tailed paired t tests showed that latencies in the rotating condition were significantly longer than in the translating condition, $t(29) = 10.96$, $p < .001$, $M = 100.70$, $d = 2.00$; latencies in the rotating condition were significantly longer than in the stationary condition, $t(29) = 13.46$, $p < .001$, $M = 153.56$, $d = 2.46$; and latencies in the translating condition were longer than in the stationary condition, $t(29) = 8.08$, $p < .001$, $M = 52.85$, $d = 1.48$.

Experiments 4a and 4b

Why would rotation play a privileged role in the production of silencing? Our proposal is that because an MS ring (or square or cylinder) is perceived as a coherent object, the locations of its changing elements are first represented with reference to object-centered axes, then located to space through combination with the externally referenced position of the whole ring and continuously updated representations that describe the alignment between internal and external axes. These extra steps create a steep climb for attributing detected changes, with strong silencing as a consequence. In Experiment 4, we seek to mitigate the challenge by obviating the need to update internal and external alignment, anticipating that such a manipulation should dampen silencing. We do so by introducing a patterned background. The pattern allows us to create visible background rotation in synchrony with a rotating ring of dots.

Experiment 4a

Method. The details of Experiment 4a were identical to Experiment 1a, except as described.

Experiment link. Experiment 4a can be viewed online with a web browser at https://www.qw.perceptionresearch.org/motion_silencing_exp_demo/motion_silencing_exp_4_demo.html.

Participants. We tested a new group of 31 undergraduates until we obtained data from 30 participants who met our inclusion criteria.

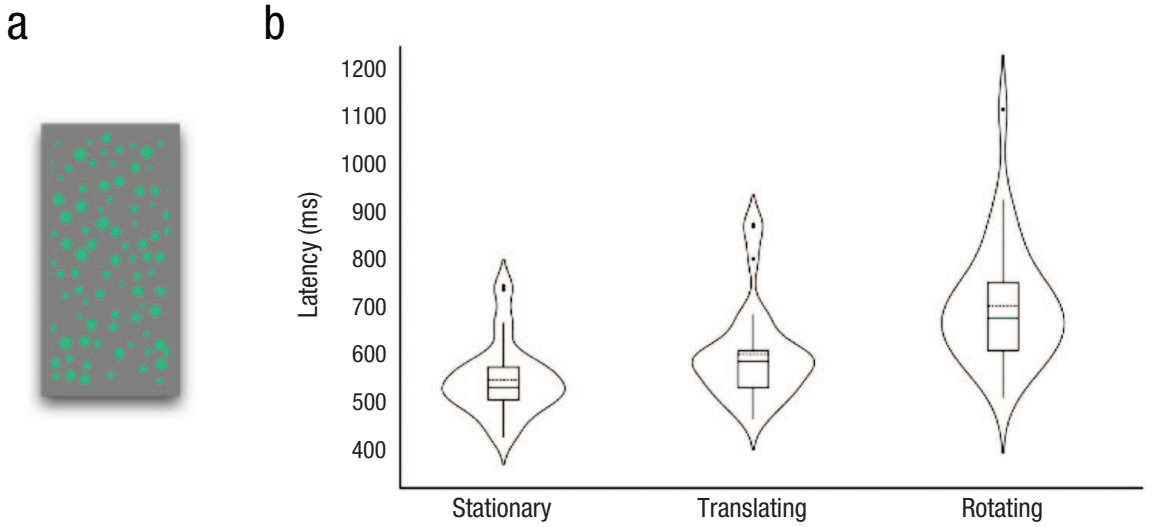


Fig. 6. (a) The stimulus used in Experiment 3b. In one-third of trials, all the dots in both columns were stationary and dots changed size in only one of them. In another one-third of trials, dots in each column translated in the same direction horizontally at the same speed. In the remaining one-third of trials, 50% of the dots in each column translated to the left and 50% translated to the right, which produced a rotating cylinder percept. The task was identical to previous experiments. Results are shown as (b) violin plots for latency against motion type. Solid lines and dashed lines indicate medians and means, respectively. Experiment 3b can be viewed online with a web browser at https://www.qw.perceptionresearch.org/Color_motion_perception_33/motionSilence_exp_33.html.

Stimuli and procedures. Experiment 4a was closely modeled on Experiment 1a. The only difference was that a background with a pattern replaced the gray background in some trials.

The experimental design was 2 × 3: Each trial could include either a stationary ring of dots or a rotating ring of dots (i.e., two ring conditions: stationary ring, rotating ring). And each trial could include one of three background types: a gray background, a stationary patterned background, or a rotating patterned background.

When rotation was present (for a ring, a background, or both) the speed was set to 90° per second. Each condition was repeated 60 times, so the experiment included a total of 360 (randomly distributed and counterbalanced) trials per participant.

Reaction time and accuracy validation. We analyzed 10,370 trials with correct responses and response latencies between 200 ms and 2,000 ms.

Results. We predicted that when the background and the ring rotate, they would produce less silencing than when the ring rotates on an unmoving patterned background. Note that the prediction here is that the addition of extra motion to the stimulus would reduce the degree of silencing. A 2 × 3 repeated-measured ANOVA showed a main effect of ring motion on latency, $F(1, 176) = 47.55$, $p < .001$, $\eta^2 = 0.20$. There was also a main effect of background type on latency, $F(1, 176) = 13.86$, $p < .001$, $\eta^2 = 0.058$, with no interaction between ring and background, $F(1, 176) = 1.085$, $p = .299$, $\eta^2 = 0.0046$. A planned one-tailed paired t test showed that latencies in response to a rotating ring on a rotating patterned background were significantly shorter than when the patterned background was stationary, $t(29) = 4.59$, $p < .001$, $M = 27.29$, $d = 0.84$. A rotating pattern behind a rotating ring reduced silencing of color changes on the ring. Figure 7b shows the latency results for the rotating ring conditions as a function of background type. For comparison, response latencies for the stationary ring conditions are also shown. These conditions were included in the experiment out of concern that the rotating background might in itself make detecting changes more difficult, which would work against the predicted effect of faster detection for a rotating ring with a rotating (textured) background compared with a rotating ring with static (textured) background. Indeed, the figure suggests that a rotating background alone did slow latency to response. Combined with the presence of the gray background conditions, this washed out the presence of an interaction. But the predicted key effect emerged nonetheless.

Experiment 4b

Method. Details of Experiment 4b were identical to Experiment 4a, except as described.

Experiment link. Experiment 4b can be viewed online with a web browser at https://www.qw.perceptionresearch.org/Color_motion_perception_32/motionSilence_exp_32.html.

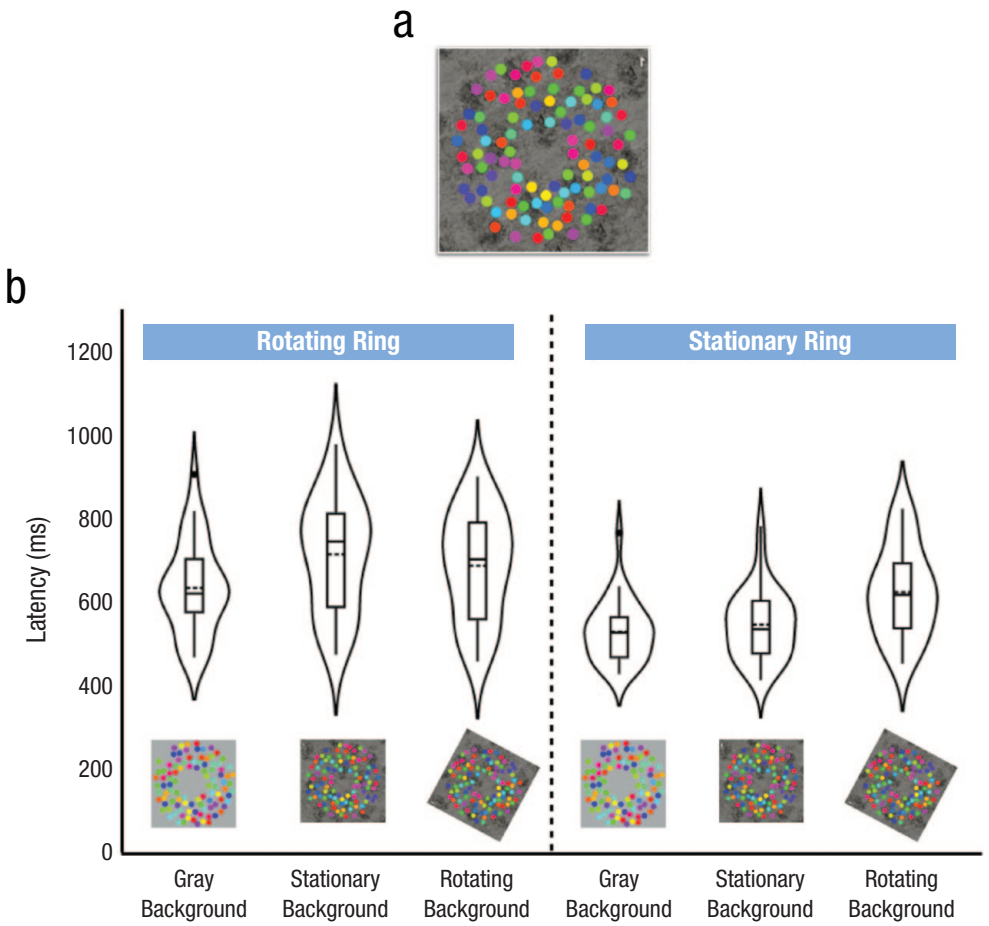


Fig. 7. (a) The stimulus used in Experiment 4a. (b) Response latencies to rotating rings as a function of background type. Results are shown as violin plots for latency against motion type. Solid lines and dashed lines indicate medians and means, respectively. Experiment 4a can be viewed online with a web browser at https://www.qw.perceptionresearch.org/motion_silencing_exp_demo/motion_silencing_exp_4_demo.html.

Participants. A new group of 30 participants was tested.

Stimuli and procedures. The stimuli in Experiment 4b differed from those in Experiment 4a in only one way: In each the trial, the RGB values for all the 100 dots were set to rgb(5,200,133). During a trial, the dots within one and only one ring changed size continuously at a rate of 30 pixels per second. Each dot was initialized with a size randomly chosen between 4.5 and 12.5 pixels. The same six conditions were tested in Experiment 4b as in Experiment 4a.

Reaction time and accuracy validation. We analyzed 9,978 trials with correct responses and response latencies between 200 ms and 2,000 ms.

Results. In Experiment 4b, A 2 × 3 repeated-measured ANOVA showed a main effect of ring motion on latency, $F(1, 176) = 50.364$, $p < .001$, $\eta^2 = 0.214$. There was also a main effect of background type on latency, $F(1, 176) = 5.449$, $p = .0207$, $\eta^2 = 0.023$. There was no significant interaction between ring motion and background type on latency, $F(1, 176) = 3.015$, $p = .0843$, $\eta^2 = 0.013$. A planned one-tailed paired t test showed that latencies in the rotating patterned background were significantly shorter than in the static pattern background, $t(29) = 4.013$, $p < .001$, $M = 51.37$, $d = 0.733$. Figure 8b shows the latency results for the rotating ring conditions as a function of background type.

General Discussion

We employed a novel method to characterize the qualities of motion that induce MS. The method asks participants to identify which ring in a pair comprises changing elements. An advantage of this approach is that it does not ask participants to directly report the rate or intensity with which they perceive changes;

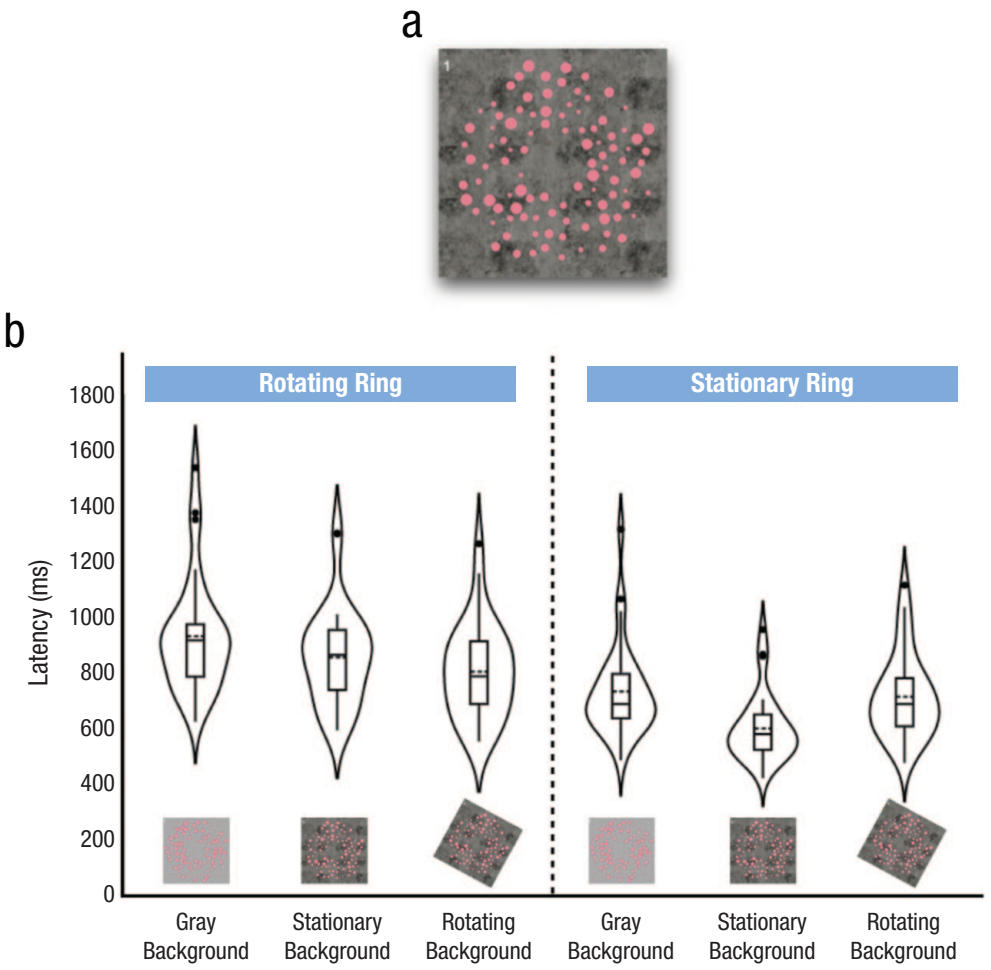


Fig. 8. (A) The stimulus used in Experiment 4b. (B) Response latencies to rotating rings as a function of background type. Results are shown as violin plots for latency against motion type. Solid lines and dashed lines indicate medians and means, respectively. Experiment 4b can be viewed online with a web browser at https://www.qw.perceptionresearch.org/Color_motion_perception_32/motionSilence_exp_32.html.

instead, it indexes illusion strength via the latency to discriminate stimuli.

To summarize what was found, (a) MS has measurable consequences on discrimination between a changing and a nonchanging stimulus (Experiment 1); (b) rotational motion produces more silencing than nonrotational motion (Experiments 2 and 3), even when rotation is purely perceptual, absent in the fact-of-the-matter kinematics (Experiment 3); and (c) when rotation appears as a general property of the environment, as opposed to an exclusive property of an object, then silencing is reduced (Experiment 4). These findings were obtained exclusively by testing Johns Hopkins University undergraduates. Future research should investigate the generizabiltiy of the findings in a broader population.

The results contravene the proposal that MS arises from a "detector speed limit": that MS is caused whenever objects move through detectors faster than the detectors can process color (or other) changes. This account is inconsistent with effects of motion type: that translation around a square produces less silencing than the rotation of a square (Experiment 2) and that perceived structural rotation produces more silencing than its constituent translation (Experiment 3). It is also inconsistent with background rotation reducing silencing (Experiment 4), a device that is orthogonal to the speed at which an element passes through a detection field.

Instead, we propose that MS is an attribution failure that arises from the challenges inherent to location representation in the presence of motion. When motion occurs in ways that promote a structured and organized representation, the challenge is exacerbated, producing the strongest silencing. A result consistent with this view appeared in one previous study, where silencing was stronger in a set of dots that constituted an upright walking person, compared with the same upside down (Poljac et al., 2012). Presumably, the upright structure

induces representations of dot positions relative to the rest of the body and also relative to an external frame of reference.

We interpret the current experiments similarly: The position of any one of the 100 elements in an MS display can be represented in one of two ways: relative to the object that they jointly define—an internally referenced frame—or relative to an external reference frame. Our proposal is that rotation can create disagreement between external and internal reference regarding the presence (or absence) of location changes. These disagreements increase uncertainty about how to attribute detected changes, producing silencing as a result.

This account explains the results as follows: Conditions that include a rotating object on a static background—the classic stimulus, the rotating square, and the structure-from-motion cylinder—produce the most silencing because they involve elements whose positions change relative to the external reference but not the internal one. Conditions with translating items—along the perimeter of a square or within the confines of a structure-from-motion inducer—include position changes when referenced both externally and internally, therefore causing less or no silencing. And a patterned rotating background creates a scenario in which background and internally referenced motion are coaligned, such that element position remains stable in both reference frames, reducing silencing.

More generally, we conclude that a ring stimulus is represented compositionally—assembled from different representational pieces—as a unified object that can be located in space by reference to external axes and with parts located by reference to object-centered axes. An additional piece of the representation is a description of how the object-centered axes align with the external axes. For example, an object-centered *y*-axis might be noted as aligned with the external vertical at one moment, and an update following rotation might describe the same object-centered *y*-axis as possessing a +20° rotation relative to the external vertical.

This kind of composite allows for a representation in which the object as a whole remains stable—with all its parts in the same places relative to one another—even as its parts occupy new locations in external space. A composite is also the underlying format for computer-assisted design. (In PowerPoint, for example, one can create an arrow using the rightward head selector, and the selected "rightward" label will remain so affixed when one rotates the arrow by 180°.) And composite representations have been used to explain working memory for oriented objects (Gregory & McCloskey, 2010; McCloskey, 2009; McCloskey et al., 2006) as well as neuropsychological conditions (McCloskey et al., 1995; Vannuscorps et al., 2022); for detailed discussion, see McCloskey (2009).

In a sense, the application of composite representation schemes to the performance of orientation memory connects it to motion processing, because orientation is a property that stands in relation to past and possible rotational motion. Yet such representations have not been suggested as constituents in the active perception of rotation, which is more typically discussed in terms of lower-level detectors thought to support the perception of motion in general (Cavanagh & Favreau, 1980). But certain facts are consistent with the perception of rotation relying on higher-level and composite representations. These include single-neuron (Sakata et al., 1986) and functional magnetic resonance imaging studies (Podzebenko et al., 2005) that have isolated rotation-specific responses in parietal areas and research on aperture problems that suggests that motion integration is form dependent and complex (Allard & Arleo, 2022). The current results therefore suggest, first, that MS does not originate with processing limitations and, instead, that it reflects the representational challenges of perception. Second, these results suggest that the active perception of rotation recruits multilayered representations of whole objects.

Transparency

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Author Contributions

Qihan Wu: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Visualization; Writing – original draft; Writing – review & editing.

Jonathan I. Flombaum: Conceptualization; Investigation; Methodology; Project administration; Supervision; Writing – review & editing.

Declaration of Conflicting Interests

The author(s) declared that there were no conflicts of interest with respect to the authorship or the publication of this article.

Open Practices

All the reported experiments were preregistered with aspredicted.org. Experiment 1a: https://aspredicted.org/4YJ_YYT. Experiment 2a: https://aspredicted.org/1TG_ZCN.Experiment 3a: https://aspredicted.org/C3V_CVP. Experiment 4a: https://aspredicted.org/WY9_NYK. Experiments 1b through 4b: https://aspredicted.org/F6J_XSH. All data and analysis code have been made publicly available via ResearchBox and can be accessed at https://researchbox.org/1888&PEER_REVIEW_passcode=GDKYEY. All experiments were run on the web. Links to each individual experiment are provided together with the methodological detail. In addition, illustrative demonstrations can be viewed as follows. (1) The basic illusion in the ring condition (as employed in Experiment 1a): https://qihan.visualthinkingresearch.com/motionSilencing/demo/motionSilence_demo_ring.html. (2) Rotating and translating square stimuli (Experiment 2a) contrasted side-by-side: https://qihan.visualthinkingresearch.com/motionSilencing/demo/motionSilence_demo_square.html.

(3) Structure-from-motion cylinder versus translating dots within the cylinder column (Experiment 3a): https://qihan.visualthinkingresearch.com/motionSilencing/demo/motionSilence_demo_cylinder.html. (4) Rotating rings on a rotating pattern background versus a static pattern background (Experiment 4a): https://qihan.visualthinkingresearch.com/motionSilencing/demo/motionSilence_demo_BG.html. This article has received the badge for Preregistration. More information about the Open Practices badges can be found at http://www.psychologicalscience.org/publications/badges.



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