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The "Double Ring Illusion": The Physical Constraint of Solidity Shapes Visual Processing

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Who does not like visual illusions? Not only do they offer a wondrous experience to viewers, but they also compellingly reveal the inner workings of our visual system. Out of the myriad of existing illusions, however, rarely are they produced thanks to priors about the *physics* of our world. Here, we present a novel illusion of this kind—the Double Ring Illusion—which demonstrates that a representation of the physical constraint of *solidity* (i.e., objects cannot pass through one another) shapes perception. Thus, when viewing ambiguously rotating rings that are compatible with multiple interpretations, the percept is strongly altered by the solidity constraint: Observers predominantly perceive the interpretation respecting solidity rather than the alternative interpretation where solidity is violated. A series of experiments first confirmed that observers reliably experienced this illusion. We then demonstrated that the effects of the illusion influence orthogonal perceptual judgments of object width, thus ruling out decision-level processes as a driver of these effects. Furthermore, we showed that the solidity constraint shapes visual processing even when the stimuli are unambiguous thanks to additional motion and depth information. And finally, we found that the visual system predictably makes use of solidity even in contexts other than the Double Ring Illusion. Together, these results demonstrate the existence of a robust prior for solidity in visual processing, guiding the computations of object motion and interaction.

Public Significance Statement

Object solidity is a fundamental constraint of our physical world and ubiquitous in human experience: For instance, we regularly see objects bouncing off the floor or resting on the table instead of passing through one another. However, while the visual system has been shown to incorporate a range of physical assumptions such as friction, gravity, and Newtonian mechanics, no study we know of has demonstrated that solidity is integrated in the visual system as a prior governing objects' behaviors. In this context, we report a surprising finding that object solidity indeed shapes visual processing.

Keywords: intuitive physics, visual illusion, object perception, motion perception, contact mechanics

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The study is preregistered at https://osf.io/6pjqy/?view_only=2a1f9bbaa5894031a0f76f0a8c824e71 (Experiment 1), https://osf.io/dw468/?view_only=b81fcd08f9774f17b2566eab6be8a9c5 (Experiment 2), https://osf.io/68cfk/?view_only=4126fa94b0974f3091bc92f49b0fcd84 (Experiment 3), https://osf.io/hk85n/?view_only=ac1d07e540394ddf922adda7e48fd3b8 (Experiment 4), and https://osf.io/c6rs7/?view_only=f64245af1bae4cfc9430c04514e97a83 (Experiment 5). The data and demonstrations in the present article were presented at the 2022 and 2023 Vision Sciences Society Meeting and the 2022 European Conference on Visual Perception. The Double Ring Illusion participated and was awarded third place in the 2021 "Best Illusion of the Year Contest" by the Neural Correlate Society.

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Illusions are a "window" into understanding human perception, as they can elegantly and straightforwardly reveal the inner mechanisms underlying our perceptual systems (Coren & Girgus, 1978; Gregory, 1997). Thus, for instance, the Ebbinghaus illusion demonstrates that size estimation is modulated by objects in the surroundings (Choplin & Medin, 1999; Coren & Miller, 1974; Massaro & Anderson, 1971), and the checker-shadow illusion shows that the perceived brightness of surfaces takes into account lighting conditions (Adelson, 1993, 1999). However, no illusion—to our knowledge—reveals the influences of *intuitive physics* on perceptual processing. In this context, we present a novel visual illusion—the "Double Ring Illusion"—which demonstrates that the visual system incorporates a representation of the physical constraint of *solidity* (i.e., that objects cannot pass through one another), which in turn shapes our perception of object motion.

Introducing the Double Ring Illusion

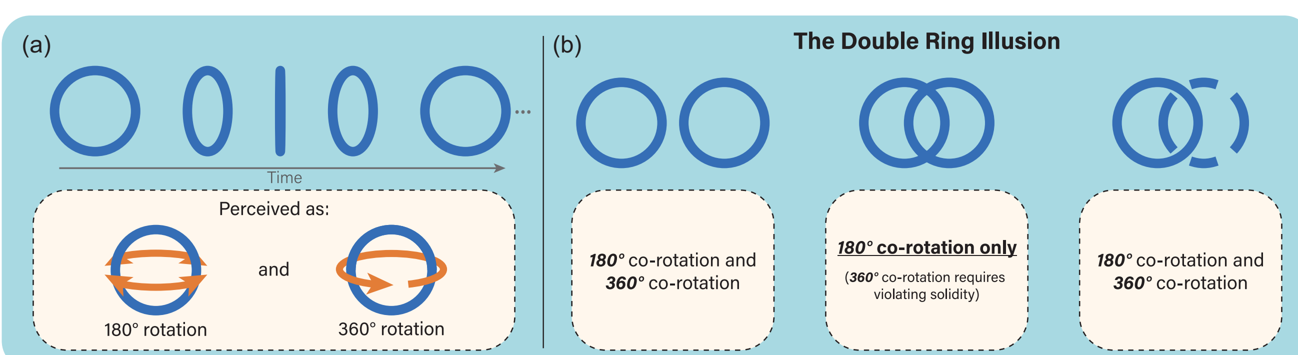
The Double Ring Illusion consists of a pair of ambiguously rotating rings (Figure 1a) whose perceived motions are altered by the solidity constraint. When the rings are separated (Figure 1b, left; Supplemental Animation S1), they are perceived as multistable, alternating between interpretations: 360° corotations (continuously clockwise or counterclockwise) and 180° corotations ("flipping" back and forth). The solidity constraint becomes relevant if the rings are positioned closer such that they partially overlap (e.g., with their centers separated by one radius's distance; Figure 1b, middle; Supplemental Animation S2)—because the 360° corotation interpretation would require the rings to occasionally pass through each other, thus violating the solidity constraint. Remarkably, 360° corotation percepts are strongly suppressed under this configuration: Such overlapping rings predominantly appear to move in 180° corotations, bouncing back as they seem to contact each other. Furthermore, if there are gaps on one of the overlapping rings such that the other ring could pass through the gaps (Figure 1b, right; Supplemental Animation S3)—removing possibilities of solidity violations—then the multistable percept is restored. We encourage readers to experience the effect themselves by viewing the Supplemental Animations (or by visiting https://www.daweibai.com/double_ring_illusion/demo.html). This illusion shows that the visual system uses a representation of the physical constraint of solidity to compute ambiguous object motion: When the stimuli are compatible with multiple interpretations, the interpretation respecting the solidity constraint (i.e., 180° corotation) is strongly preferred over the one that violates it (i.e., 360° corotation); and when no solidity violation is possible in any interpretation, this preference is disrupted.

Relation to Previous Work

Object solidity is a ubiquitous aspect of human visual experience: We routinely perceive objects bouncing on the floor or leaning against or resting atop one another. It is thus important for our organism to internalize such a basic constraint in order to help represent the physical world. Indeed, research on preverbal infants has shown that solidity is one of the earliest emerging physical representations in the human mind (Baillargeon, 1987; Baillargeon & DeVos, 1991; Baillargeon et al., 1985; Spelke et al., 1992), which has even led many developmental psychologists to posit that the representation of solidity is part of our genetic endowment (Carey, 2009; Spelke et al., 1992; Spelke & Kinzler, 2007). In one classic study, 2.5-month-olds were shown a ball rolling behind an occluder; after the occluder was removed, infants were surprised if the ball reappeared beyond the barrier (which implied that the ball had passed through it; Spelke et al., 1992). However, these early-emerging representations are generally thought to be achieved by infants' *reasoning* capacities (Lin et al., 2021, 2022) and not as part of the priors within their visual system (Spelke, 2022, 2024).

In contrast to the extensive research showing preverbal infants' capacities for *reasoning* about object solidity, studies on *perception* have not found clear evidence that this physical constraint is incorporated in the visual system. First, a series of studies investigated solidity in the context of biomechanics (Chatterjee et al., 1996; Shiffrar & Freyd, 1990, 1993). Participants in these studies were shown two alternating images of a human body with a body part in different positions (e.g., an arm on two sides of a knee), which

Figure 1
The Double Ring Illusion



Note. (a) The percept of an ambiguously rotating ring is multistable, alternating between 360° and 180° rotations. (b) The Double Ring Illusion. (Left) A pair of such rings is also perceived as multistable when separated. (Middle) Crucially, a simple manipulation changes how the rings are perceived: If they partially overlap, they are predominantly perceived as moving in 180° (co)rotations. The interpretation of 360° corotation—which requires the rings to violate the solidity constraint (i.e., objects cannot pass through one another)—is rarely, if ever, seen. (Right) This preference is disrupted if there are gaps on the rings, removing possibilities of collision. Readers can experience this illusion by viewing the Supplemental Animations S1–S3 or at https://www.daweibai.com/double_ring_illusion/demo.html. See the online article for the color version of this figure.

led them to explicitly report perceiving the body part in repeating motion (i.e., apparent motion). Under (and only under) long stimulus onset asynchronies, participants reported favoring the curved and physically plausible path over the shortest path, which required one body part to pass through another. However, this effect disappeared if the body parts were replaced with inanimate objects: Across all stimulus onset asynchrony levels, participants consistently favored the shortest path, which violated solidity (Chatterjee et al., 1996). Furthermore, if the stimuli consisted of a wooden mannequin that resembled a human body, then again participants preferred the solidity-respecting path under long stimulus onset asynchronies. Therefore, these findings support the existence of a prior for solidity *only* as a biomechanical constraint for the human body, and this solidity prior may *not* play a role in general intuitive physics for objects.

Another line of investigation on solidity's role in visual processing comes from illusions displaying obvious violations of solidity. One such illusion is the "Pulfrich solidity illusion" (Bai & Strickland, 2023; see also the "Pulfrich double pendulum illusion," Leslie, 1988; Wilson & Robinson, 1986): When looking through a neutral-density filter over one eye (with both eyes open) at a pendulum swinging behind a solid bar, observers perceive the pendulum passing through the bar while moving in an elliptical path—thus violating solidity. The elliptical path is caused by the fact that darker images are processed more slowly, and the resultant interocular discrepancy displaces the pendulum's perceived depths (known as the "Pulfrich effect"; Burge et al., 2019; Morgan & Thompson, 1975; Pulfrich, 1922; Rogers & Anstis, 1972). Another illusion of this kind is a variant of the "Ames window illusion" (Ames, 1951), in which a rotating trapezoidal window appears to oscillate back and forth, even if a ruler is fixed perpendicularly through the window. As the ruler is seen as rotating toward one direction and the window as oscillating, these two objects appear to occasionally pass through one another. Critically, however, these illusions do not demonstrate that the visual system is insensitive to the solidity constraint; instead, they only show that in specific contexts, the representation of solidity *can* be overridden by other motion and depth cues and priors (e.g., stereoscopic depth cues and the assumption that window frames are rectangular). In other words, if these cues were made weaker, solidity may turn out to affect how the objects are perceived. In sum, despite numerous investigations in the past decades, there has been no clear evidence (that we know of) showing whether or not the visual system incorporates solidity in its computations as a constraint for object physics.

The Present Study

In a series of five preregistered experiments, we tested and explored the influence of solidity on object motion perception. We first verified that observers do experience the Double Ring Illusion (Experiment 1) and, importantly, that this effect is not explained by postperceptual decision making (Experiment 2). Next, we explored in various ways the generality of solidity's influence on object motion perception. One, we asked whether solidity continues to constrain visual processing when the stimuli's motion is not ambiguous thanks to other sources of depth and motion information (Experiments 3 and 5). Two, we sought to replicate the effect in a display distinct from the Double Ring Illusion (Experiments 4 and 5).

Experiment 1: The Double Ring Illusion

We first measured how people perceive the Double Ring Illusion in perhaps the most direct way: We simply showed observers the displays (i.e., separated, overlapping, or gapped rings) and asked them to choose from two options the one that best depicted the rings' rotations (Figure 2a).

Method

Transparency and Openness

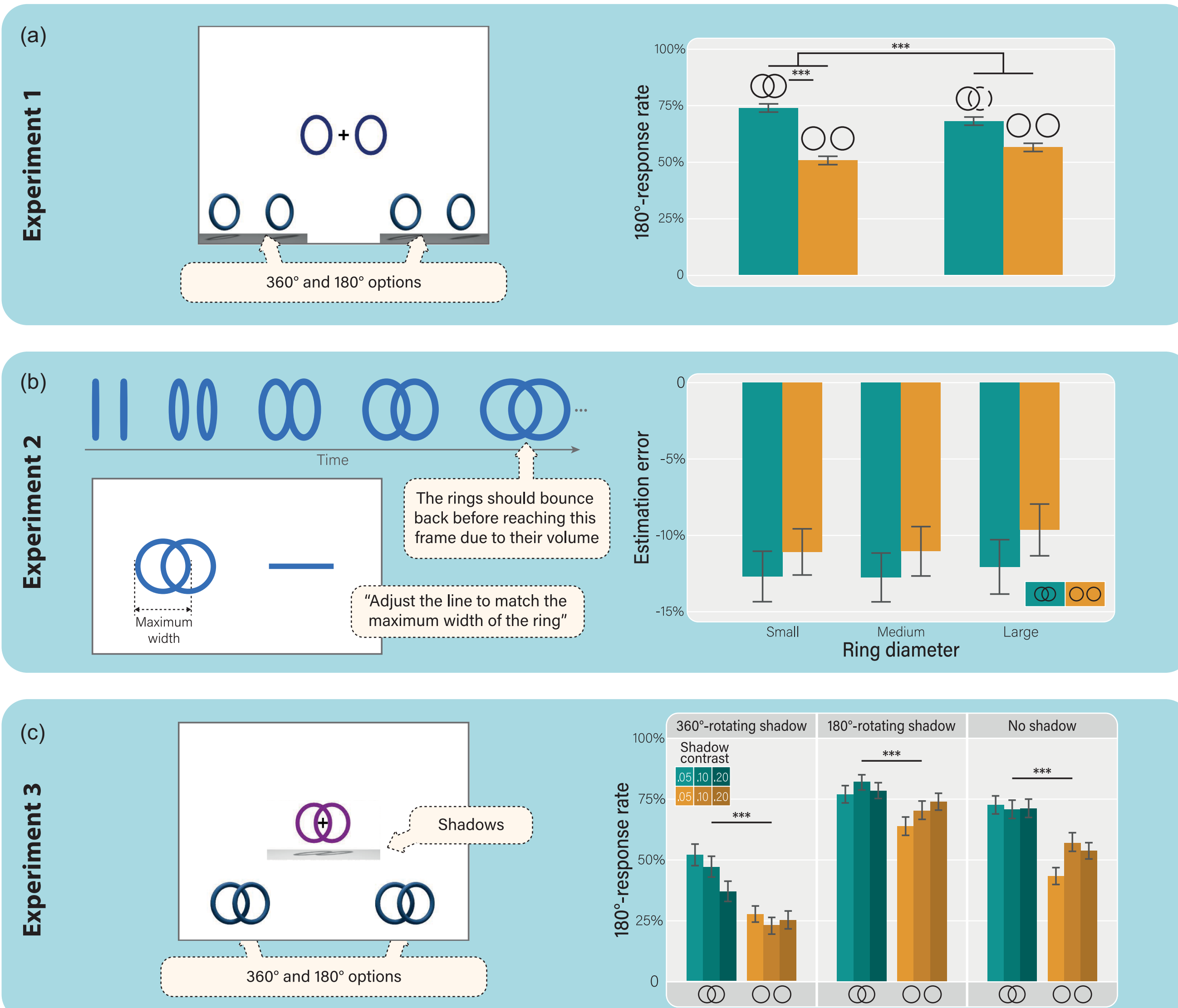
The experiment's design and analyses were preregistered for all experiments. The raw data, preregistration documents, and R scripts for data exclusion and analyses are all publicly available on the Open Science Framework at https://osf.io/6pjqy/?view_only=2a1f9bbaa5894031a0f76f0a8c824e71 (Experiment 1), https://osf.io/dw468/?view_only=b81fcd08f9774f17b2566eab6be8a9c5 (Experiment 2), https://osf.io/68cfk/?view_only=4126fa94b0974f3091bc92f49b0fcd84 (Experiment 3), https://osf.io/hk85n/?view_only=ac1d07e540394ddf922adda7e48fd3b8 (Experiment 4), and https://osf.io/c6rs7/?view_only=f64245af1bae4cfc9430c04514e97a83 (Experiment 5).

Observers. Four hundred observers (matching the preregistered sample size) participated in this experiment via the Prolific online platform (Palan & Schitter, 2018) for monetary compensation, with the sample size preregistered before data collection began. The preregistered sample size was calculated with R, with a power of .80 and α of .05 based on pilot data. Observers were excluded (with replacement) according to three preregistered criteria. First, observers failing to correctly answer any of three trivial attention questions (e.g., "Which continent is Canada located in? North America, Asia, or Europe?") were rejected. Second, observers who did not respond "Yes" to the feedback question "Were the videos displayed smoothly?" at the end of the experiment were rejected. Third, responses with reaction times more than three times the median absolute deviations away from the median in each condition were rejected. All observers gave consent prior to participation. They were not asked about their gender, sex, or ethnicity. This research complied with all ethical regulations of and was approved by the *Conseil d'évaluation éthique pour les recherches en santé* and adhered to the Declaration of Helsinki principles and guidelines.

Apparatus. Upon agreeing to participate, observers were redirected to a website to complete the experiment. The stimuli were presented, and data were collected via custom software developed with a combination of HTML, CSS, JavaScript, PHP, and the JsPsych plugins (de Leeuw, 2015). The photorealistic options were rendered with Blender 2.82 (https://www.blender.org/). Observers completed the experiment on a laptop or desktop computer.

Stimuli. The stimuli consisted of two untextured circles whose width changed following a sinusoidal function relative to time. Such a display corresponded to the 2D projection of 3D rings rotating at an angular speed of 1.2π/s. The rings appeared in one of three colors in each trial (navy [red-green-blue values: 0,0,128], dark red [red-green-blue values: 139,0,0], or dark green [red-green-blue values: 0,100,0]), and their radius was 50 px with a thickness of 11 px. The "gapped" rings had four gaps each subtending an angle of 0.17π. Each trial showed two rings, which could be (a) separated, with their centers

Figure 2
Experiments 1–3



Note. (a) Experiment 1. (Left) Observers viewed a pair of overlapping, separated, or gapped rings and indicated how the rings appeared to move by choosing from two options displaying respectively 360° and 180° corotations. (Right) Results showed a preference for 180° corotations with overlapping rings, and this preference was disrupted when the rings were separated or gapped. (b) Experiment 2. (Left) Participants saw overlapping or separated rings of three different diameters and adjusted the length of a line to match the maximum apparent width of one of the rings. (Right) Results showed that overlapping rings (compared to separated rings) led to lower estimations of the maximum width of the ring. (c) Experiment 3. (Left) We generalized the viewing context to unambiguous stimuli by adding another source of depth and motion information—shadows—under the rings, and observers performed the same task as Experiment 1. (Right) Results showed that overlapping rings consistently led to more 180° percepts than separated rings, regardless of whether the shadows contradicted (360°-rotating shadows) or agreed with (180°-rotating shadows) the solidity constraint. Error bars depict standard error. See the online article for the color version of this figure.
*** $p < .001$.

separated by three times the radius of a ring, (b) overlapping, with their centers separated by one radius, or (c) overlapping but one of the rings was gapped. A black fixation cross was displayed at the center of the stimuli. At the bottom of the screen, two photorealistic response options were displayed, one showing two rings moving in 180° corotations and the other one showing two rings moving in 360° corotations. These displays were not ambiguous due to the presence of various motion and depth cues such as shades and occlusion. Note that under this design, the rate of 180° responses was unlikely to reach 0% or 100%, because the motion that observers saw might not be available (e.g., if observers saw 360° clockwise rotation, but only 360° counterclockwise rotation was an available option, they might opt for the 180° option). While counterrotations were also possible interpretations of the stimuli, such options were not shown, because research has shown that when multistable stimuli are presented close to each other, they tend to elicit the same percept (e.g., *co*rotation instead of *counter*rotation; Eby et al., 1989; Grossmann & Dobbins, 2003; Ramachandran & Anstis, 1983).

Procedure. At the beginning of each trial, the center of the screen was covered by a dynamic noise mask for 1.5 s, intended to minimize the influence of the stimuli from the previous trial. Afterward, a pair of rotating rings and a fixation cross appeared at the center of the screen. Observers were instructed to stare at the fixation cross while attending to the rings. The response options were shown 4 s after the rings appeared, and observers clicked on the option that best depicted the rings' motion. The animation was looping, and the trials advanced only after a response. Observers were divided into two groups: One group saw separated and overlapping rings, and the other group saw separated and gapped rings. Each observer saw 10 trials, shown in randomized order.

Results and Discussion

All analyses followed the preregistration. Most crucially, the results (Figure 2a) showed a significant two-way interaction of Separated/Nonseparated × Subject Group (mixed analysis of variance), $F(1, 398) = 12.20$, $p < .001$, $\eta^2 = 0.01$, 95% CI [0.05, 0.18]. In the "separated and overlapping" group ($N = 200$), separated rings elicited on average 50.8% ($SD = 0.256$) of 180° responses, significantly less than with overlapping rings ($M = 74.0\%$, $SD = 0.260$; paired t test), $t(199) = 10.312$, $p < .001$, $d = 0.729$, 95% CI [0.19, 0.28]. In the "separated and gapped" group ($N = 200$), separated rings elicited on average 56.6% ($SD = 0.268$) of 180° responses, significantly less than with gapped rings ($M = 68.2\%$, $SD = 0.260$; paired t test), $t(199) = 4.844$, $p < .001$, $d = 0.343$, 95% CI [0.07, 0.16]. Additionally, observers who saw overlapping rings were more likely to give the 180° response than those who saw gapped rings (unpaired t test), $t(398) = 2.195$, $p < .05$, $d = 0.219$, 95% CI [0.01, 0.11].

These results confirmed the phenomenological experience of the Double Ring Illusion: Observers predominantly perceived 180° corotations when viewing overlapping rings, and this preference was disrupted when the rings were separated or gapped such that no solidity violation could potentially occur. Note also that the difference between gapped and separated rings is likely explained by the visual system automatically filling in the gaps via amodal completion (Michotte et al., 1964; Singh, 2004). Indeed, when disconnected objects move in concert—as the segments of the gapped ring do—they give rise to the percept of one unitary object (rather than independent parts; Kellman & Cohen, 1984; Kellman & Shipley, 1991; Kellman & Spelke, 1983; Valenza et al., 2006). Therefore, the visual system may treat the gapped rings as full rings. Mere proximity difference (i.e., greater proximity of rings in the gapped condition compared to the separated condition), on the other hand, is unlikely to explain the difference between the perception of these rings, because proximity is known to lead to stronger coupling (i.e., the same percept for both rings, favoring *co*rotation over *counter*rotation; Eby et al., 1989; Grossmann & Dobbins, 2003; Ramachandran & Anstis, 1983), but not *altering* the whole percept of the couple (e.g., changing from 360° rotation to 180° rotation).

Taken together, these results revealed a prior for solidity in the processing of ambiguous object motion: In the absence of sufficient visual input that can help determine object motion, the visual system resorts to the physical constraint of solidity.

Experiment 2: Excluding Response Strategy

It is possible that participants in Experiment 1 *reasoned* postperceptually that the overlapping rings should not pass through each other, thus responding that they moved in 180° rotations, instead of truly *perceiving* such. To address this potential issue, we designed a task that was orthogonal to such a possible response strategy. Here, participants estimated the maximum apparent width of one of the rings (by adjusting the length of a line to match it). The rationale was that the moment at which overlapping rings bounce back should occur *before* reaching the frontoparallel plane, as the rings should collide at a slight angle due to their thickness (Figure 2b). Therefore, these rings should in principle never appear to be at their full apparent width (i.e., on the frontoparallel plane); and this limited range of motion could lead to a lower estimation of the maximum apparent width of the rings. If, however, the overlapping rings are perceived as moving in 360° corotations, such an effect should not occur. Here, reasoning about solidity (or even about the rings' motions) is irrelevant to the simple task of estimating width; so if we find the effect, it is best explained as observers truly perceiving the overlapping rings in 180° corotation, instead of as resulting from any response strategies.

Method

This experiment was identical to Experiment 1 except as noted.

Participants

Eighty new participants (matching the preregistered sample size) took part. The preregistered sample size was calculated with a power of .95 (higher than in Experiment 1, due to the otherwise low sample size) and α of .05. Participants were excluded (with replacement) according to four preregistered criteria, including the three criteria from Experiment 1 and a debrief question asking participants to rate (from 1 to 100) how much they were able to stay focused through the experiment, with participants giving a response below 60 rejected.

Stimuli

The stimuli consisted of a pair of rotating rings positioned on the left half of the screen (without a fixation cross). The rings were slightly thicker (14 px) than those of Experiment 1. On the right half of the screen, a horizontal line (with a thickness of 10 px) was displayed. The line's length could be adjusted when the left or right arrow keys were pressed. In each trial, the pair of rings was either separated or overlapping, with the rings in one of three sizes (45 px, 50 px, or 55 px in radius). As Experiment 1 established that the proximity of the rings cannot explain the differences in perceived object motion, we did not include the condition with gapped rings.

Procedure

In each trial, participants adjusted the length of the horizontal line by pressing the left and right arrow keys on the keyboard. The trials advanced only after the participants finished adjusting and pressed the spacebar. Each participant saw 48 trials, shown in randomized order, including two ring configurations (overlap/separated) and three ring sizes (small/medium/large).

Results and Discussion

All analyses followed the preregistration. The results (Figure 2b) revealed that participants' (N = 80) estimation of the maximum width of overlapping rings ($M = -12.5\%$ compared to the correct size, $SD = 0.146$) was significantly lower than that of separated rings ($M = -10.6\%$ compared to the correct size, SD = 0.141; paired t test), $t(79) = 3.313$, $p = .001$, $d = 0.370$, 95% CI [0.01, 0.03]. The rings' size did not modulate the effect: The two-way interaction of Small/Medium/Large × Separated/Overlapping was not significant (repeated measure analysis of variance), $F(2, 158) = 0.81$, $p = .45$, $\eta^2 = 0.002$.

Given that reasoning about solidity is irrelevant to the basic task of estimating width, these results suggested that participants indeed automatically *perceived* the overlapping rings as moving in 180° corotations (as opposed to merely *reasoning* about them moving in that way).

Experiment 3: Generalizing to Unambiguous Stimuli With Shadows

Having investigated how solidity influences the perception of *ambiguous* stimuli, we then asked whether this representation is still operative in more general and *unambiguous* contexts—where other obvious sources of motion and depth information are present. To test this, we added shadows corresponding to those of rings moving in 360° corotation or in 180° corotation (Figure 2c). Shadows have been shown to serve as a depth cue for dynamic objects (Katsuyama et al., 2011; Kersten et al., 1996, 1997) and should therefore specify the rings' rotation direction—thus, in principle, the visual system no longer needs to make use of the solidity constraint.

Method

This experiment was identical to Experiment 1 except as noted.

Observers

One hundred ninety-one new observers (matching the preregistered sample size) took part.

Stimuli

Shadows were added below the ambiguous rings (which were identical to those of Experiment 1). The shadows were rendered in Blender 2.82 by first creating a pair of rotating 3D rings with stationary overhead surface lighting; the shadows were cast onto a horizontal and uniform gray surface below the rings, and these shadows (as well as the surface) were outputted as frames. The frames were then adjusted to match one of three root-mean-square contrast levels (0.05/0.10/0.20) and added below the ambiguous rings in the experiment. The shadows corresponded to rings moving in 180° corotations or 360° corotations. In a contrast condition, there were no shadows on the gray surface. The response options did not have shadows.

Procedure

Observers performed the same task as in Experiment 1. Each observer received 24 trials, including two ring configurations (separated/overlapping), three shadow types (360°/180°/no shadow), and one of three levels of shadow contrast (0.05/0.10/0.20). The trials were shown in randomized order.

Results and Discussion

Results showed that when shadows were present (i.e., excluding the "no shadow" condition), overlapping rings ($M = 62.3\%$, SD = 0.203) were still perceived significantly more often as moving in 180° corotations than separated rings ($M = 47.1\%$, $SD = 0.181$; paired t test), $t(190) = 7.903$, $p < .001$, $d = 0.572$, 95% CI [0.11, 0.19]. Importantly, even with shadows *contradicting* solidity (i.e., 360°-rotating shadows), observers saw 180° corotation significantly more often for overlapping rings ($M = 45.0\%$, $SD = 0.348$) than for separated rings ($M = 25.0\%$, $SD = 0.272$; paired t test), $t(190)$ = 7.900, $p < .001$, $d = 0.572$, 95% CI [0.15, 0.25]. This was also true with shadows *in agreement* with solidity (i.e., 180°-rotating shadows): Overlapping rings ($M = 79.2\%$, $SD = 0.260$) were more often perceived as moving in 180° corotations than separated rings ($M = 69.4\%$, $SD = 0.303$; paired t test), $t(190) = 4.057$, $p < .001$, d = 0.294, 95% CI [0.05, 0.15]. Moreover, the results replicated the findings of Experiment 1: In the absence of shadows, overlapping rings ($M = 71.6\%$, $SD = 0.298$) elicited a higher 180° response rate than separated rings ($M = 51.4\%$, $SD = 0.301$; paired t test), $t(190)$ = 6.561, $p < .001$, $d = 0.475$, 95% CI [0.14, 0.26]. (We note that our analyses slightly deviated from the preregistered plans. We did find the predicted effects for all the planned analyses. However, upon careful consideration, we opted to not describe some of them here, as they were actually not crucial to the key hypothesis. Instead, we reported above two analyses that we later deemed as important: [a] "overlapping" versus "separated" with both shadow types collapsed and [b] the same comparison but with 180°-rotating shadows. The p values for these two analyses were exceedingly small [1.0×10^{-12} and 7.3×10^{-5}, respectively], indicating that their significance was extremely unlikely to be due to fluctuations.)

If the solidity prior is overridden by shadows, overlapping and separated rings should lead to the same result patterns, but this was not the case: Observers were still more likely to perceive 180° corotations when viewing overlapping rings than separated rings—and this was true both when shadows were contradicting (i.e., 360°-moving shadows) and in line with (i.e., 180°-moving shadows) the solidity cue. Thus, the solidity representation remained robust in the presence of shadows, continuing to constrain the perception of object motion. These results provided evidence for a more general influence of the solidity representation on object motion processing: Even when facing displays endowed with information that can help determine motion, the visual system still factors in the solidity constraint.

Experiment 4: Further Generalizing to Another Display …

As physical objects in our world come in various shapes and move in various trajectories, any physical constraint should not be restricted to a specific object shape (e.g., rings) and motion pattern (e.g., self-rotation), but instead it should be generalizable to other contexts. In the present experiment, we therefore tested the solidity prior in a display completely different from the Double Ring Illusion along these physical dimensions. This display consists of a disc oscillating along a linear trajectory (Figure 3a). The disc could be perceived as a ball moving elliptically (in depth) or linearly (on the frontoparallel plane). Crucially, a vertical bar either intersected the disc's path—introducing a potential solidity violation (Supplemental Animation S4)—or was separated from it (Supplemental Animation S5). Such a display may be reminiscent of an aforementioned study by Chatterjee et al. (1996), where subjects looking at apparent-motion displays tended to report perceiving the object as moving in a straight path that violated solidity, rather than a curved path that respected it. But crucially, this study lacked a contrast condition in which no solidity violation was possible—for example, with no object obstructing the moving object's straight path. In such a condition, the curved path could actually turn out to be perceived *even* less often, suggesting that the representation of solidity does play a part. Therefore, key to the present experiment is whether the solidity-preserving path (i.e., the elliptical one) is more often perceived when a bar obstructs the ball's straight path compared to the contrast condition where the bar is not "in the way" of the ball.

Method

This experiment was identical to Experiment 1 except as noted.

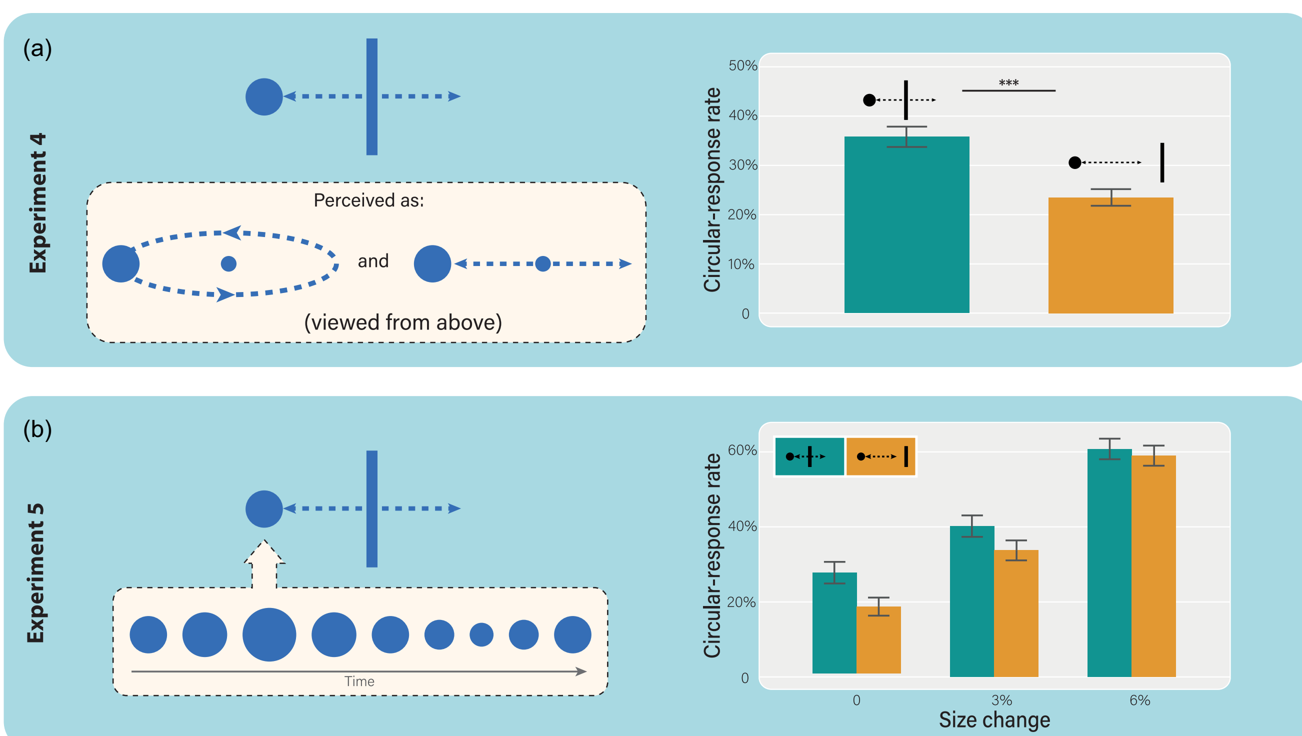
Observers

One hundred thirty-nine new observers (matching the preregistered sample size) took part. Observers were excluded (with replacement) according to the same four preregistered criteria as in Experiment 2.

Stimuli

The stimuli consisted of a moving disc, a fixation cross, and a static vertical bar. The disc was untextured (with a radius of 11.7 px), oscillating along a horizontal 158 px-long path with its speed following a sinusoidal function relative to time (with an angular speed of 1.2π/s). The fixation cross was displayed 33 px above the center point of the disc's path. The vertical bar was untextured (with a width of 13 px) and in the same color as the disc (in one of three colors, the same as the rings in Experiment 1). The bar was positioned either along the perpendicular bisector of the disc's path ("overlap" condition) or away from it (120 px of horizontal distance away from the center of the disc's path; "separate" condition). At the

Figure 3
Experiments 4 and 5



Note. (a) Experiment 4. (Left) An oscillating disc can be perceived as a ball moving elliptically in depth or linearly in the frontoparallel plane. (Right) Results showed that observers saw the elliptical trajectory more often when a bar overlapped with the disc's path than when the bar was separated. (b) Experiment 5. (Left) Another motion and depth cue—optical size changes—was added: The ball expanded and shrunk in a manner that was consistent with elliptical trajectory in depth. (Right) Results showed that the elliptical trajectory was more often perceived in the "overlapping" condition than in the "separated" condition. Error bars depict standard error. See the online article for the color version of this figure.
*** $p < .001$.

bottom of the screen, two photorealistic response options were displayed, one showing a ball moving linearly on the frontoparallel plane and the other one showing a ball moving elliptically in depth. The options also showed a cylinder corresponding to the position of the vertical bar.

Procedure

In each trial, observers viewed a display and chose the best matching option. Each observer saw 12 trials, including the two configurations (overlap/separated), shown in randomized order.

Results and Discussion

All analyses followed the preregistration. The results (Figure 3a) showed that observers (N = 139) chose the elliptical option significantly more often when the bar overlapped with the disc's path (M = 35.8%, SD = 0.245) than when the bar was separated (M = 23.5%, SD = 0.199; paired t test), $t(138) = 5.317$, $p < .001$, d = 0.451, 95% CI [0.08, 0.17].

These results provided evidence from yet another display type that solidity is embedded in object motion processing, suggesting a general influence of solidity as opposed to one that may be restricted to specific object types or motion types.

Experiment 5: … and With an Additional Motion and Depth Cue—Optical Size Changes

Is the solidity representation in this display type (an oscillating disc and a bar) robust to additional information that disambiguates the motion trajectory (just like the Double Ring Illusion is robust to shadow information)? Here, another motion and depth cue—optical size changes—was introduced to the disc, such that the disc expanded and shrunk in a way that corresponded to a ball moving elliptically in depth (Figure 3b; see Supplemental Animations S6 and S7 for demonstrations with a size change level of 6%). Like the shadows in Experiment 3, optical size changes specify the ball's motion, as previous research has established that such information serves as a cue for dynamic objects' changes in depth (Regan & Beverley, 1978, 1979; Regan et al., 1986).

Method

This experiment was identical to Experiment 1 except as noted.

Observers

One hundred new observers (matching the preregistered sample size) took part. Observers were excluded (with replacement) according to the same four preregistered criteria as in Experiment 2.

Stimuli

The disc's radius changed following a sinusoidal function of time, such that at moment t, its radius was $r + \sin(t) \cdot r \cdot \mu$ (r was the baseline radius, 11.7 px, the same as the disc in Experiment 4; μ was the size change level: 0, 3%, or 6%). A filler condition was also added, where the bar was positioned like in the "overlap" condition of Experiment 4 but was in a color different from the disc. The bar alternated between being in front of and behind the disc each time the disc reached it (as if occluding and being occluded by the disc).

Procedure

In each trial, observers viewed a display and chose the best matching option. Each observer saw 54 trials, including three size change levels (0/3%/6%) and three spatial configurations (separated/overlap/filler), shown in randomized order.

Results and Discussion

All analyses followed the preregistration. Results (Figure 3b) showed that observers (N = 100) gave the "elliptical" response significantly more often when the bar overlapped with the disc's path (M = 42.8%, SD = 0.223) than when the bar was separated (M = 37.3%, SD = 0.191; paired t test), $t(99) = 2.738$, $p < .01$, d = 0.274, 95% CI [0.02, 0.09]. The effect was not modulated by size change level, as indicated by the nonsignificant two-way interaction of Separated/Overlapping × 0/3%/6% Size Change (repeated measures analysis of variance), $F(2, 198) = 2.084$, $p = .127$, $\eta^2 = 0.003$.

These results showed that solidity continues to play a role in object motion perception in the presence of optical size changes. Note also that the presence of the bar cutting through the disc's path should in theory make it more difficult to notice size changes in the first place, thus leading to *less* "elliptical" responses than when the bar was away from the disc—if solidity was not taken into account by the visual system. Yet, the opposite pattern of results was found, demonstrating the robustness of the solidity representation.

General Discussion

Through a novel visual phenomenon—the Double Ring Illusion—we demonstrated and explored the influence of the solidity constraint on visual perception. First, our experiments confirmed that observers reliably experienced this illusion: When viewing motion displays compatible with multiple interpretations, observers predominantly perceived the interpretations respecting solidity over interpretations violating it, and this visual preference was disrupted when no possible violation of solidity could occur (Experiment 1). Second, and importantly, using a task that is orthogonal to reasoning about solidity, we demonstrate that the effect of solidity on object motion processing cannot be explained by decision-making-level processes but truly reflects how people automatically perceive the displays (Experiment 2). Third, we then further generalized the effect of solidity to other viewing contexts in various ways. Thus, in the presence of disambiguating motion and depth cues like shadows (Experiment 3) and optical size changes (Experiment 5), as well as in a display different from the Double Ring Illusion (Experiments 4 and 5), solidity continues to shape the perception of object motion. These findings provide novel insights into how our organism integrates the physics of the world as automatic perceptual heuristics, using these representations to guide the processing of objects and their interactions.

Solidity as a Puzzling Missing Piece From Vision's Intuitive Physics

One might wonder whether our visual system can embed such sophisticated representations like solidity or even intuitive physics in general. Indeed, physical representations may seem so high-level—as they could potentially be the subject of high school physics classes—that they were historically studied only in the context of deliberate reasoning capacities (e.g., in tasks asking people to draw objects' future trajectories from static depictions; Kubricht et al., 2017; McCloskey, 1983). Recent work in vision science, however, has demonstrated that the visual system also incorporates many such sophisticated representations. For instance, when viewing two-object collisions, observers detect speed patterns violating Newtonian laws more easily than speed patterns respecting them (Kominsky et al., 2017). Other kinds of physical representations that have been shown to shape visual processes include spatiotemporal continuity (Erlikhman & Caplovitz, 2017; Scholl & Pylyshyn, 1999), cohesion (Mitroff et al., 2004), stability (Wong et al., 2024; Yang & Wolfe, 2020), gravity (Nguyen & van Buren, 2023), friction (Gilroy & Blake, 2004; Nguyen & van Buren, 2024), and more (e.g., Wong et al., 2023). Solidity, however, has been a puzzling missing piece from this picture, despite numerous investigations over the past decades, both theoretically (Leslie, 1988; Scholl & Leslie, 1999) and empirically (Ames, 1951; Bai & Strickland, 2023; Chatterjee et al., 1996; Shiffrar & Freyd, 1990, 1993; Wilson & Robinson, 1986). In this context, therefore, our study provides the first demonstration (that we know of) that solidity is embedded in the visual system, operating as a general physical constraint governing behaviors of objects.

What are the computations underlying the solidity constraint, and what is its relationship with other physical representations? Recently, an influential proposal posited the existence of a physics engine in the brain that is engaged during physics-related tasks (Fischer et al., 2016; Ullman et al., 2017). However, we speculate that the solidity constraint need not be part of a general physics engine. Instead, solidity can be simply represented as a "uniqueness" constraint in depth processing: If two objects overlap on the visual field, then the overlapping parts must necessarily be attributed two different depths. Such a depth-based constraint ensures that no two objects should be perceived as occupying the same space at the same time, thereby equating the solidity constraint. Therefore, investigating the neural mechanisms related to solidity could not only shed light on how this constraint is computed in the brain but also explore the limits of the general physics engine.

Constraints on Generality

While several of our experiments were designed specifically to investigate the generality of solidity's effect on object motion processing (Experiments 3–5), there remain some open questions. Why does the visual system respect solidity in some situations (as in the Double Ring Illusion reported here), whereas in other situations it allows violations of this constraint (as in the Pulfrich solidity illusion; Bai & Strickland, 2023; and in the variant of the Ames window illusion; Ames, 1951)? This is likely because the visual system is constantly weighing different sources of information—including solidity, which may be overridden by other motion and depth cues in some contexts. Future work can investigate the relative strength of the solidity representation compared to other cues. Even the perception of the relatively simple displays of the Double Ring Illusion is the product of many cues: Apart from being assumed to be solid, the rings are also perceived as having the same size and depth (even though one could be closer and smaller than the other) and as moving continuously (while they could instead be "jumping ahead" discontinuously in space). Although our further experiments explicitly explored whether solidity remains robust in the presence of other cues such as shadows (Experiment 3) and optical size changes (Experiment 5), the strengths of these cues can only be compared by quantitatively varying the strength of the solidity constraint (e.g., by varying the thickness of the rings) and the strength of a competing cue. Another open question concerns the scopes of the solidity representation. While physical objects in our world do not pass through each other, some other entities, such as gas, do not behave under this constraint. This raises the question of whether the visual system conditionally applies the solidity constraint depending on the physical state of the entity: Does vision also expect gas-like entities to not pass through one another?

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