
Solid as a rock: Solidity shapes the perception of object motion

Dawei Bai¹, Brent Strickland^{1,2}

¹ École Normale Supérieure, Département d'études cognitives, PSL Research University, Institut Jean Nicod (ENS, EHESS, CNRS), Paris, France

² Africa Business School; School of Collective Intelligence - UM6P - Rabat, Morocco

Abstract

The human visual system embeds prior expectations about physical regularities of our world. One such regularity is that of “object solidity”: Solid objects cannot pass through each other. Is object solidity internalized in the human visual system? Here we provide converging evidence across five pre-registered behavioral experiments that the adult visual system uses solidity to compute object motion. We show that when viewing ambiguous displays of moving objects that are compatible with multiple interpretations, the visual system strongly favors interpretations which respect the solidity constraint over those that violate it, and this effect is not due to post-perceptual decision biases. Further demonstrating the robustness of this effect, we discovered that even in the presence of other motion and depth cues, solidity remains robust and continues to influence motion perception. Together, our results demonstrate for the first time that the physical law of solidity guides visual processing of object motion.

We recommend readers to view the demo to experience the compelling effect themselves:
https://www.daweibai.com/solidity_ambiguous_motion/demo_sep.html.

Correspondence: dawei.bai@hotmail.com (Dawei Bai)

Our visual perception of objects goes beyond what they look like, where they are and how they move. Object perception is often also accompanied by intuitions about some aspects of the underlying physics. When observing a tower of stacked rocks, we can not only appreciate its aesthetic appeal, but also experience the “gut feeling” that it is balanced or not¹⁻³. When seeing an object thrown towards us, we are able to quickly predict its trajectory, thereby enabling us to move in place and make the catch^{4,5}. It is now accepted that the human visual system integrates prior assumptions about how physical objects should behave^{6,7}. As objects in our world follow some physical regularities and constraints, the visual system can internalize such physical regularities as priors, which then guide the processing of information in real time⁸⁻¹⁰. Thus, for example, when viewing two-object collisions, observers detect speed patterns violating Newtonian laws more easily than speed patterns respecting them¹¹, suggesting visual sensitivity to Newtonian mechanics. It is easier to find an unstable object among stable ones than vice versa, showing that object stability guides visual search¹². When tracking multiple objects, performance is not impaired if the targets occasionally move behind occluders, demonstrating that visual tracking embeds the assumption that objects continue to exist even when out of view¹³. Such processing of physical regularities is essential as it helps us to accurately represent complex and dynamic environments based on everchanging and sometimes partial sensory inputs. In the present work, we investigate one such regularity termed “object solidity”, which stipulates that one solid object cannot pass through another. We ask whether object solidity is internalized in the human visual system’s routines for parsing dynamic information.

Object solidity is an important aspect of our everyday visual experience. It is ubiquitous in our lives, as we routinely perceive objects bouncing on the floor, colliding with each other, or resting on top of one another. Moreover, solidity is a foundational physical regularity and as such, is a prerequisite for many other physical regularities. For instance, for objects to support or collide into each other, or to be grasped by our hands, the law of solidity has to be assumed first. Abundant research in preverbal infants has shown that solidity is one of the earliest-emerging physical expectations in the human mind¹⁴⁻¹⁷. In one study, 2.5-month-old infants were shown a ball rolling behind an occluder. After the occluder was removed, the infants’ looking behaviors revealed that they were surprised if the ball reappeared beyond a solid barrier (which implies that the ball had previously traversed the barrier, thus violating the law of solidity), but not if it reappeared lying in front of the barrier. However, such early-emerging expectations are generally thought to be achieved by infants’ *reasoning* capacities, as opposed to *visual* processing¹⁸. That is, infants’ expectation for solidity may be generated through a form of precocious reasoning (in a similar way that you calculate the sum of 5 and 11 or decide which stock to buy), instead of being computed by vision (in a similar way that you compute motion or depth).

While solidity has inspired extensive research about human’s precocious reasoning capacities, evidence that the visual system is sensitive to this physical constraint is mixed. One suggestive piece of positive evidence comes from a study on apparent motion¹⁹. In this study, participants viewed two alternating

images of a human body with a body part in different positions (e.g., a limb on two sides of the body). This display purportedly created apparent motion: Instead of perceiving two static instances of the body, observers perceived the body part in repeating motion. Typically, the trajectory of apparent motion is the shortest possible path (i.e., linear path). But here, under long stimulus onset asynchronies (SOAs), participants' responses favored the curved and physically plausible path, instead of the shortest path which required one body part to pass through another (and this was not the case under shorter SOAs). However, these results may not allow us to conclude that the visual system actually factors in solidity to compute object motion. First, studies have shown that under long interstimulus intervals (as was the case with long SOAs in the study in question), observers are more likely to perceive apparent motion in a curved path—even when solidity is not involved^{20,21}. Second, given that the stimuli were images of the human body, the results might not be applicable to general physical objects, particularly considering findings showing that different cortical areas are reported to be involved in the processing of physical objects as opposed to human bodies.² Thus, despite being a ubiquitous aspect of our physical world, object solidity has not been convincingly demonstrated to guide visual perception.

It is true that representations such as those of object collision and friction that logically depend on the assumption of solidity have been demonstrated to guide visual processes^{22–24}. But they still leave open the possibility that perception detects and is sensitive to specific properties in certain types of interactions (e.g., speed pattern after collision), while not representing object solidity per se. Moreover, the visual system actually accepts obvious violations of this physical law under certain real-world viewing contexts. The first context is the “Pulfrich solidity illusion”²⁵, a modified version of the Pulfrich effect²⁶. The original Pulfrich effect is created by viewing a swinging pendulum with both eyes, with one eye covered by a neutral-density filter. This setup results in an illusory percept of the pendulum moving in an elliptical path in depth, while in reality, it swings on the fronto-parallel plane. This illusion is caused by differential processing of visual information between the two eyes: Because darker images are processed more slowly, as stereoscopic depth is formed, the two fused images of the pendulum are from different moments. This results in a perceived depth that is displaced from the actual depth^{27–31}. The Pulfrich solidity illusion modifies the classic setup by positioning a horizontal solid bar in front of the pendulum such that it cuts through the illusory path. Under this setup, the pendulum appears to traverse the bar while moving elliptically. In another similar illusion, “Pulfrich double pendulum illusion”^{32,33}, two rigid pendula in separate fronto-parallel planes and swinging in opposite directions are also perceived as moving elliptically and occasionally passing through each other. These illusions suggest that object solidity can be overridden by the stereoscopic depth cue in the context of the Pulfrich effect. The second context is a variant of the “Ames window illusion”³⁴. Here, a rotating trapezoidal window appears to oscillate back and forth—even if a ruler is fixed perpendicularly through the window such that they rotate together. As the window is seen as oscillating and the ruler as rotating in one direction, observers occasionally perceive the ruler traverse the window, creating an illusory solidity

violation. This illusion suggests that object solidity can be overridden by the perspectival cue of depth when they are put in competition. Thus, despite being an inviolable constraint of our daily world, object solidity is not treated as an inviolable prior by the visual system. Taking all the evidence into consideration—the absence of positive evidence and the existence of illusory solidity violations—one can even reasonably doubt whether solidity is internalized in vision at all.

In the current study, we investigated whether object solidity shapes the perception of object motion as a lens into a possible way in which vision may integrate this constraint. First, we created impoverished stimuli of moving objects that are intrinsically ambiguous and therefore are compatible with multiple interpretations. Impoverished stimuli have been widely used to reveal perceptual priors, as such stimuli minimize the role of sensory input, thus highlighting the role of internal priors. The crucial aspect of our stimuli is that, in some possible interpretations but not others, one object traverses another. We found first that the visual system predominantly prefers interpretations respecting object solidity over those violating it, suggesting that the visual system makes use of solidity to interpret ambiguous motion. The effect is so compelling that readers can experience it themselves by viewing the [demo](#). Second, this effect cannot be caused by post-perceptual decision biases, demonstrating that the solidity constraint is truly embedded in processes of visual perception. Third, we then investigated whether solidity is in play in the processing of unambiguous stimuli by introducing kinetic and depth cues. We found that even though the objects' motion is specified in the sensory input as cues like shadows or size changes are present, solidity still influences how motion is perceived. Further demonstrating the generality of the effect, the effect was consistent across two sets of distinct displays. In summary, our findings across five pre-registered experiments provide converging evidence that the visual system uses the physical law of solidity to compute object motion.

Results

Experiment 1: Solidity in Ambiguous Motion

Adult participants were shown two ambiguously rotating rings that could be interpreted as moving in 360° co-rotation (clockwise or counterclockwise) or 180° co-rotation (appearing to reverse direction when they reach the fronto-parallel plane; Figure 1A). The rings were overlapping (with their centers 1 radius' distance apart), separated (with their centers 3 radius' distance apart), or gapped (same as overlapping rings except that one of the rings had gaps, removing the possibility of collisions; Figure 1B). All rings were untextured, identical in size and color and underwent the same motions. Crucially, the 360° co-rotation interpretation in the case of overlapping rings required the rings to pass through each other, thereby violating the physical law of solidity. Hence, the key question was whether the visual system's interpretation is more biased to favor 180° co-rotation in this condition compared to the other conditions. Participants performed a 2-alternative forced choice (2-AFC) task, wherein they were asked

to choose from two options the one that better matched the perceived motion of the ambiguous rings. One option showed a pair of rings moving in 180° co-rotation and the other option showed 360° co-rotation (Figure 1B). Participants were divided into two groups, with one group receiving separated and overlapping rings, while the other group received separated and gapped rings.

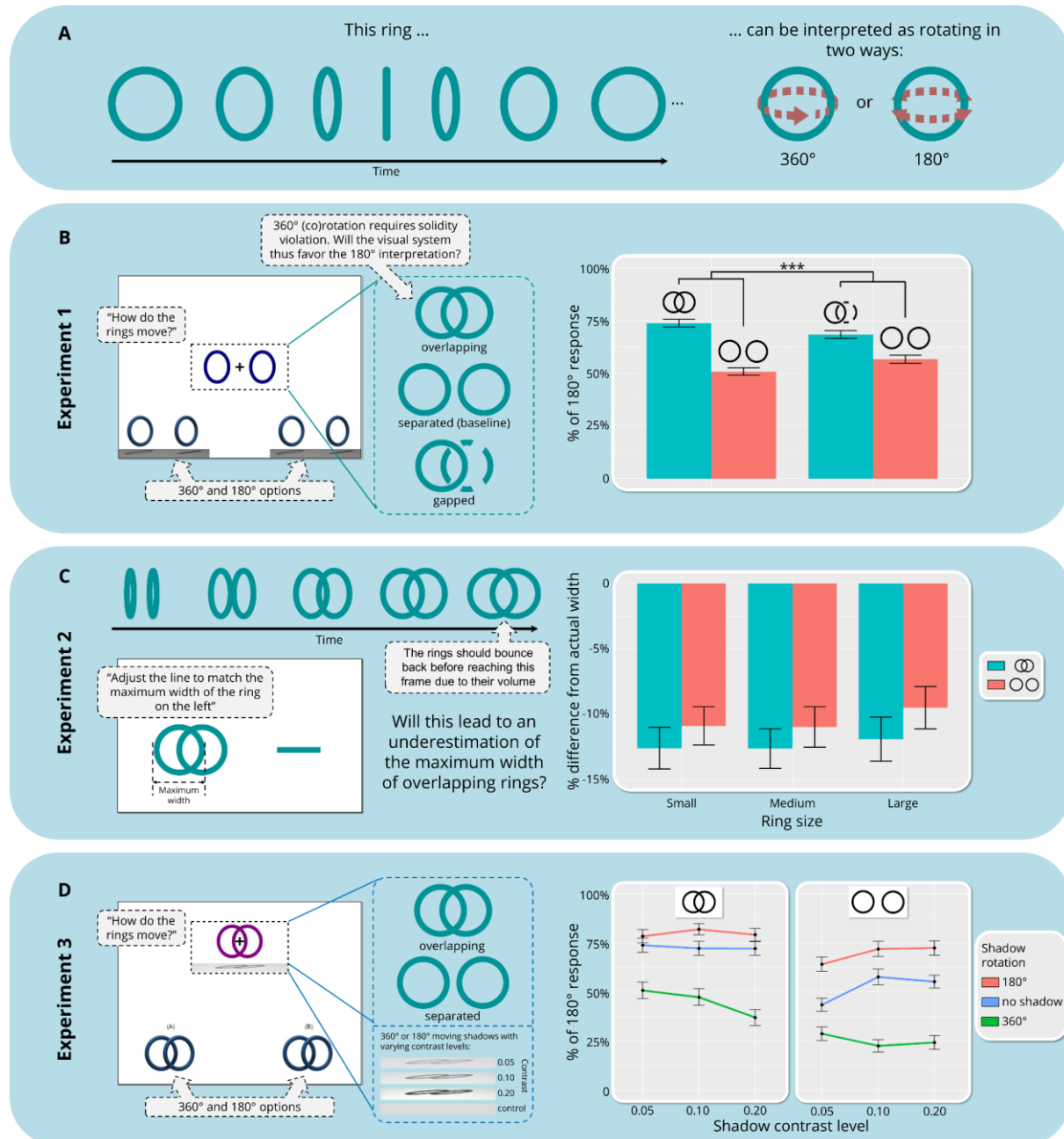


Figure 1 Experiments 1, 2 and 3. (A) Ambiguously rotating ring. A circle that changes width sinusoidally over time creates the percept of a 3D rotating ring. Its rotation is ambiguous, as it is compatible with at least two interpretations: 360° rotations, continuously counterclockwise or clockwise (not shown), or 180° rotations, “flipping” back and forth. (B) Experiment 1. How would a potential violation of solidity alter the percept of the ambiguous rings? Adult participants ($N = 404$) were presented with pairs of ambiguous rings and indicated how the rings appeared to move by choosing from two options: one demonstrating 180° co-rotation and the other 360° co-rotation. Participants were divided into two groups: One group ($N = 202$) received overlapping rings (with their

centers 1 radius' distance apart) and separated rings (3 radius' distance apart), the other group ($N = 202$) received gapped rings (1 radius' distance apart, and one ring had gaps allowing the other ring to pass through) and separated rings. Crucially, the 360° co-rotation interpretation of overlapping rings required the rings to traverse each other, thus violating solidity, whereas such violation was not possible in separated and gapped rings. The results in the baseline condition (i.e., separated rings) showed no preference for either interpretation, while the rate of 180° responses significantly increased for overlapping rings and gapped rings. Most importantly, this increase was significantly greater for overlapping rings than for gapped rings. This suggests that although all the rings underwent the same motions, they were perceived differently according to whether potential solidity violations can take place, with a preference for the interpretation that agrees with solidity. The contrast condition with gaps confirmed that the proximity of the overlapping rings cannot fully explain the effect. Readers can experience the effect themselves at http://85.90.245.160/sol-demos/demo/demo_sep.html. (C) Experiment 2. Participants in Experiment 1 may have *reasoned* at the post-perceptual stage that the rings should not pass through each other, instead of truly *perceiving* this. To address this confound, we created a task that is orthogonal to reasoning about solidity. Participants ($N = 85$) were shown overlapping or separated rings at various sizes and were asked to adjust the length of a line to match the maximum width of the ring on the left. Results showed that overlapping rings led to bigger underestimations of the maximum width of the ring than separated rings. This can be explained by the fact that the overlapping rings should bounce back before reaching the fronto-parallel plane (i.e., the moment of maximum width) due to their volume, and this limited range of motion led to an underestimation of ring width. As the task about ring width was irrelevant to solidity, the results cannot be explained by participants' post-perceptual decision bias, but only by the fact that they truly perceived the overlapping rings bouncing back when they appeared to touch. (D) Experiment 3. When facing unambiguous motion displays, does solidity continue to shape object motion perception? Disambiguating shadows were added under the rings, and participants ($N = 202$) performed the same task as Experiment 1. Each participant received overlapping and separated rings, with 180°-rotating or 360°-rotating shadows at one of the RMS contrast levels (0.05, 0.10 or 0.20), as well as a control condition without shadows. Results showed a main effect of spatial configuration despite the presence of shadows (excluding control condition): Overlapping rings led to more 180° responses than separated rings, suggesting that solidity was not overridden by the presence of shadows. Furthermore, in the presence of shadows conflicting with solidity (360°), participants still saw 180° rotation significantly more often for overlapping rings than for separated rings, suggesting that solidity remains robust and resists the contradictory shadow cue. With shadows consistent with solidity (180°), overlapping rings also elicited more 180° responses than separated rings, suggesting that solidity accumulates with the shadows cue when they are in agreement. Together, these results revealed that solidity continues to influence object motion perception even when motion is specified in the visual input. Error bars depict standard errors.

The results (Figure 1B) revealed a significant 2-way interaction of separated/non-separated \times subject group (mixed ANOVA, $F(1, 400) = 12.56$, $p = 0.0004$, $\eta^2 = 0.01$), showing that, relative to the baseline condition (i.e., separated rings), overlapping rings led to a stronger preference for 180° rotations than gapped rings. Therefore, the preference for 180° interpretation was disrupted if no violation of solidity could occur due to gaps. This result also indicated that the proximity of the rings cannot fully explain the preference for the 180° interpretation. In the “separated & overlap” group, participants ($N = 202$)

gave on average 50.8% ($SD = 0.256$) of “180°” responses when viewing separated rings, suggesting that they did not experience a preference for either interpretation. Overlapping rings led to a significantly higher 180° response rate ($M = 73.9\%$, $SD = 0.261$; paired t -test, $t(201) = 10.354$, $p < 0.0001$, $d = 0.729$). In the “separated & gapped” group ($N = 202$), separated rings elicited 56.8% ($SD = 0.269$) of “180°” responses, significantly lower than with gapped rings ($M = 68.3\%$, $SD = 0.261$; paired t -test, $t(201) = 4.809$, $p < 0.0001$, $d = 0.338$). This difference could be explained by the proximity of the rings in the “gapped” condition or by the fact that the visual system might automatically complete the gaps (thus leading to a solidity based disambiguation in some cases). Additionally, participants who saw overlapping rings were more likely to give the 180° response than those who saw gapped rings (unpaired t -test, $t(402) = 2.160$, $p = 0.03$, $d = 0.215$). These results demonstrated the presence of a physical prior for solidity in the visual processing of ambiguous motion. In the absence of sufficient visual input that can help determine object motion, the visual system resorts to the physical law of solidity to guide interpretation, favoring the interpretation respecting the physical law of solidity over the interpretation that violates it.

Experiment 2: Perception or Post-perceptual Reasoning?

It is possible that participants in Experiment 1 *reasoned* at the post-perceptual stage 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 confound, we designed a task that was orthogonal to the solidity constraint to make it impossible that participants’ reasoning caused them to respond in line with the solidity constraint. Here, participants were asked to estimate the maximum width of one of the rotating 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 they reach the fronto-parallel plane, as the rings should collide at an angle due to their thickness (Figure 1C). In other words, if the solidity constraint is in effect, the overlapping rings should never appear to be at their full width (i.e., on the fronto-parallel plane). This limited range of motion could consequently lead to an underestimation of the maximum width of the overlapping rings, but not (or less so) in the case of separated rings. Here, there was no reason for participants to make use of solidity at the decision-making level to perform the task, because (1) they were asked about the width of a ring, instead of its motion, (2) they were asked about a single ring, instead of both and (3) the color and size of the rings were also varied across trials to make it even harder for participants to guess the purpose of the test. Therefore, if we find the predicted effect, it can only be explained by the fact that the solidity constraint automatically operates within the visual system regardless of the relevance of the task.

The results (Figure 1C) revealed that indeed, participants ($N = 85$) underestimated the maximum width of overlapping rings ($M = -12.4\%$, $SD = 0.144$) more than that of separated rings ($M = -10.4\%$, $SD = 0.138$; paired t -test, $t(84) = 3.618$, $p = 0.0005$, $d = 0.392$). Furthermore, the 2-way interaction between

ring size (small/medium/large) and ring configuration (overlap/separated) was not significant (repeated measure ANOVA, $F(2, 168) = 0.83$, $p = 0.44$, $\eta^2 = 0.002$), suggesting that this effect was consistent across all three sizes. These results suggested that participants saw the overlapping rings bounce back before reaching the fronto-parallel plane, which led to a bigger underestimation of the width of the ring compared to when the rings were separated. As solidity was tested implicitly in a way that is orthogonal to the higher-level reasoning about solidity, this effect can only be explained by mechanisms within the visual system.

Experiment 3: Solidity and Shadows

If the stimuli are not intrinsically ambiguous, does solidity still constrain motion perception? When the visual input already provides enough information to determine motion, the visual system in principle no longer needs to make use of solidity. In other words, will solidity be “vetoed” by other kinetic and depth cues, or will it continue to contribute to motion perception? We tested this by adding to Experiment 1’s stimuli shadows that corresponded to those of rings moving in 360° rotations or 180° rotations (Figure 1D). It has been shown that the visual system uses moving shadows to extract depth information in dynamic objects^{35–37}. As a result, shadows could render the rings unambiguous in respect of 180° or 360° rotation. Participants ($N = 202$) were divided into three groups. Each group received one of three contrast levels of shadows (root mean square contrasts of 0.05, 0.10 and 0.20), two spatial configurations (separated and overlapping rings), as well as 180° moving shadows, 360° moving shadows and a control condition without shadows.

First, the effect in Experiment 1 was replicated: In the absence of shadows, overlapping rings ($M = 72.2\%$, $SD = 0.296$) elicited more 180° responses than separated rings ($M = 52.2\%$, $SD = 0.299$; paired t -test, $t(201) = 6.821$, $p < 0.0001$, $d = 0.480$). Next, if solidity is overridden by shadows, the same results should be observed for overlapping and separated rings, but this was not the case. Results revealed a main effect of ring configuration when shadows were present (i.e., with control condition excluded): Overlapping rings ($M = 62.6\%$, $SD = 0.200$) were perceived significantly more often as moving in 180° rotations than separated rings ($M = 47.8\%$, $SD = 0.187$; paired t -test, $t(201) = 7.980$, $p < 0.0001$, $d = 0.561$). The results also showed a main effect of the two types of shadow rotations compared to when shadows were absent (control condition), confirming that participants did make use of the shadow cue to help determine motion. Specifically, 180° shadows ($M = 75.1\%$, $SD = 0.225$) led to more 180° responses than control condition ($M = 62.3\%$, $SD = 0.212$; paired t -test, $t(201) = 7.645$, $p < 0.0001$, $d = 0.538$), while 360° shadows ($M = 35.7\%$, $SD = 0.265$) led to fewer 180° responses than control condition (paired t -test, $t(201) = 11.354$, $p < 0.0001$, $d = 0.799$).

Next, we explored how solidity interacts with shadows when they contradict or agree with each other. The results showed that with shadows contradicting solidity (i.e., 360° shadows), participants still saw 180° rotation significantly more often for overlapping rings ($M = 45.3\%$, $SD = 0.351$) than for separated

rings ($M = 25.7\%$, $SD = 0.282$; paired t -test, $t(201) = 7.932$, $p < 0.0001$, $d = 0.558$). Thus, when solidity was in conflict with the shadow depth cue, it continued to constrain motion perception. This was also true with shadows in line with solidity (i.e., 180° shadows), as overlapping rings ($M = 80.0\%$, $SD = 0.257$) led to more 180° responses than separated rings ($M = 70.3\%$, $SD = 0.302$; paired t -test, $t(201) = 4.112$, $p < 0.0001$, $d = 0.289$). This suggests that solidity and 180° shadows accumulate to create a strong percept when they provide converging information about motion.

Taken together, our results provided evidence for a general influence of the solidity prior on object motion processing, as they suggest that even when facing displays endowed with information that can help determine motion, the visual system still factors in solidity to compute motion. Solidity and shadows combine to determine motion: When solidity is in harmony with shadows, they accumulate to form a strong percept, and when solidity is contradicted, it remains salient and robust, resisting the contradictory information.

Experiment 4: Generalizing to other displays

We further explored the robustness of the prior for solidity and its influence in object motion perception by testing it in a different display. In this display, a ball oscillates horizontally along a linear trajectory with its speed following a sinusoidal function of time (Figure 2A) and could in principle be interpreted as moving circularly in depth or linearly on the fronto-parallel plane. Crucially, a vertical bar either intersected the ball's path ("overlap" condition)—introducing a potential solidity violation—or was separated from it ("separated" condition), without the possibility of a solidity violation. Each participant received both conditions and performed a 2-AFC task by choosing from two options showing linear motion and circular motion. The question was thus whether observers would be more likely to perceive the circular interpretation in the "overlap" condition than in the "separated" condition (Figure 2B).

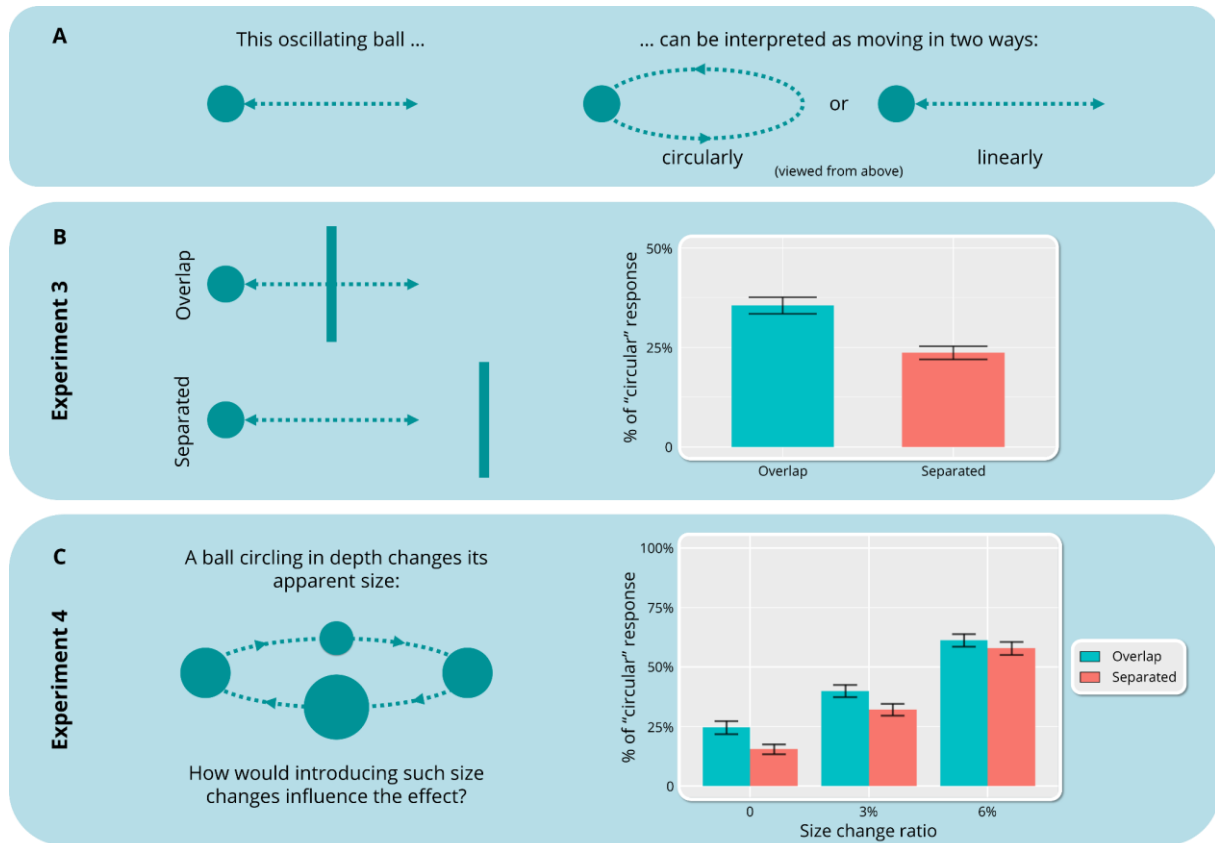


Figure 2 Experiment 4 and 5. (A) Ambiguously moving ball. An oscillating ball whose speed follows a sinusoidal function of time can be interpreted as moving circularly in depth or linearly in the fronto-parallel plane. (B) Experiment 3. Adult participants ($N = 140$) saw an oscillating ball and a static bar that either perpendicularly intersected the ball's path or was separated from it. Participants were asked to look at the fixation cross and indicate how the ball appeared to move by choosing from two options, one demonstrating circular motion and the other linear motion. Here, the linear trajectory in the "overlap" condition required solidity violation. Results showed a significantly higher "circular" response rate in the "overlap" condition than in the "separated" condition, suggesting that the visual system factors in solidity when computing the ball's motion. (C) Experiment 4. Changes in optical size were introduced to the ball, which expanded and shrunk in a manner that was compatible with circular motion in depth. In each trial, the maximum diameter increase or decrease was 0 (i.e., no size change), 3% or 6% compared to the mean diameter. Again, participants ($N = 115$) consistently gave more circular responses for the "overlap" condition than for the "separated" condition across the three size variation levels. The results demonstrated that in the presence of the disambiguating cue of optical size changes (and their absence), object solidity continues to bias motion perception. Error bars depict standard errors.

Our data showed that indeed, when the bar overlapped with the ball's path, participants ($N = 140$) were significantly more likely to choose the circular option ($M = 35.5\%$, $SD = 0.246$) than when the bar was away from the ball ($M = 23.7\%$, $SD = 0.198$; paired t -test, $t(139) = 5.125$, $p < 0.0001$, $d = 0.433$). These results provided evidence from 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 event types.

Experiment 5: Solidity and Optical Size Changes

Here we introduced another motion cue—optical size changes—to the oscillating ball. Notice in the previous experiment that, in contrast to the rings in Experiment 1, the visual system did not treat the ball’s motion as fully ambiguous, because participants predominantly perceived the baseline condition (“separated” condition) as moving in a linear fashion. This is likely due to the fact that the ball’s size remained constant, which the visual system interpreted as indicating constant depth (the previous results therefore also demonstrated the robustness of solidity when it is in competition with the no-size-change cue). Just like shadows, previous research has shown that changes in optical size serve as a cue for depth changes in dynamic objects^{38–40}. Specifically, an expanding object is perceived as approaching, while a shrinking object is perceived as receding. In the present experiment, we introduced size changes to the oscillating ball in a way that matched the size changes of a ball moving circularly in depth (Figure 2C). Each participant saw three levels of size change (3% or 6% of diameter change and a control condition without size change), as well as two spatial configurations (bar separated from vs. overlapping with the ball’s path).

Results revealed a main effect of spatial configuration: When the bar overlapped with the ball’s path, participants ($N = 115$) gave more the “circular” response ($M = 41.9\%$, $SD = 0.213$) than when the bar was separated from the ball ($M = 36.6\%$, $SD = 0.191$; paired t -test, $t(114) = 2.864$, $p = 0.005$, $d = 0.267$). There was no evidence that the effect was modulated across the three size change levels, as indicated by the non-significant interaction of overlap/separated \times 0/3%/6% of size change (repeated measures ANOVA, $F(2,228) = 2.643$, $p = 0.073$, $\eta^2 = 0.003$). Evidently, participants were consistently more likely to favor the percept in agreement with solidity when a potential solidity violation can take place than when no solidity violation can occur. Thus, solidity continues to play a role in motion perception even in the presence (and absence) of optical size changes. Note also that the presence of the bar cutting through the ball’s path should in theory make it more difficult to detect size changes, which would hypothetically lead to less “circular” responses than when the bar was away from the ball—if solidity was not taken into account by the visual system. Yet, the opposite pattern of results was found, providing evidence for the salience of the solidity cue.

Discussion

In this study, we conducted five pre-registered experiments using two sets of distinct motion displays to demonstrate that adult vision utilizes the physical law of solidity to compute object motion. We found that solidity shapes how dynamic object displays are interpreted not only when they are ambiguous but also in the presence of disambiguating motion and depth cues like shadows and optical size changes. Our findings shed light on the visual processing of objects and their spatial relationships—ubiquitous

and fundamental aspects of our everyday lives. Such priors are essential to our organism as they could help us to veridically perceive and successfully navigate the physical environment.

Experiment 1 showed that when facing dynamic 3D objects that intrinsically lack motion and depth information (and are thus compatible with multiple interpretations), the visual system relies on solidity to determine object motion. We used a pair of rotating rings that appear multistable when separated, and introduced potential solidity violations to this display by positioning the rings in a partially overlapping manner. This manipulation drastically altered the likelihood of perceiving the rivaling interpretations. Evidently, participants experienced a dominant percept, favoring the interpretation consistent with the solidity constraint over the interpretation that violates it. To rule out the possibility that this effect was solely due to the proximity of overlapping rings, we also included a contrast condition with gapped rings, which disrupted the perceptual preference. Experiment 2 addressed the concern that this effect might be due to post-perceptual reasoning. We created a task that implicitly and indirectly tested solidity and found that the effect persisted, confirming that it is truly perception that computes the solidity constraint. In Experiments 3-5 we generalized the visual context by adding other disambiguating motion cues like shadows and optical size changes (and the absence thereof). Here, the visual input provided sufficient information to determine motion—thus in principle, the visual system did not have to make use of the prior knowledge of solidity. Our results nevertheless showed that solidity continued to influence processing of object motion. We manipulated the shadows (Experiment 3) and optical size changes (Experiment 4 and 5) in consistent and conflicting ways with regard to the solidity cue. Our data showed that solidity accumulated with other sources of motion information when they were consistent with each other and remained salient and robust when it was conflicted by other cues. Further demonstrating the generality of the effect, our experiments used two sets of distinct displays which led to the same effect. Taken together, our findings provide converging evidence that the basic physical law of object solidity is incorporated in the visual processing of 3D object motion.

Object solidity has been a missing piece in studies of intuitive physics, which has garnered significant attention in the last four decades from both vision scientists and developmental psychologists. Notably, these two camps of researchers have observed striking parallels between findings in infant reasoning capacities and those in adult vision^{41–43}: Physical expectations that have been identified to emerge in the first half year of life as part of infants' precocious reasoning abilities tend to also be shown to operate in adult vision. This is perhaps because some physical regularities are so important that they are the first to be grasped by infants' reasoning capacities and are also embedded in the adult visual system in order to help us successfully navigate and interact with the environment. Specifically, on one side, research on infant reasoning has revealed that babies as young as 3.5 to 5 months readily expect objects to continue to exist when occluded^{14–17} and to maintain coherence as they move^{44–46}, that 4.5-to-6.5-month-olds are sensitive to spatiotemporal properties of causal collision events^{47,48}, and that 2.5-to-5-month-olds expect objects to not pass through each other^{14–17}. On the other side, research on adult vision has

demonstrated that the visual system is capable of representing dynamic objects moving through occlusion^{13,49,50}, is sensitive to object cohesion when viewing persisting objects⁵¹, and is tuned to Newtonian mechanics in causal collision events^{11,22,23,52,53} (and unsurprisingly other physical regularities beyond the infant repertoire such as balance^{3,12}, friction²⁴ and so on). Therefore, object solidity constitutes a missing piece in the diverse landscape of physical priors underlying adult vision: Despite being a basic physical law of our world and deeply ingrained in infants' reasoning capacities, solidity has not been demonstrated to operate in adult vision. Our results, therefore, provided the first piece of evidence to fill this void.

How to explain visual illusions where apparent violations of solidity take place? As mentioned earlier, there exist at least two such illusions: the “Pulfrich solidity illusion”^{25,32,33}, where a swinging pendulum appears to pass through a solid bar when viewed with a neutral-density filter over one eye, and the variant of the Ames window illusion³⁴ where a ruler and a trapezoidal window rotating together appear to move through each other. While these illusions support the hypothesis that solidity can be overridden by stereoscopic and perspectival depth cues, they do not show that the solidity cue is non-existent. This is because these illusions are isolated cases with single parameter settings: It is possible that due to the solidity constraint, the presence of the solid bar in fact reduces the Pulfrich effect, and that the presence of the ruler reduces the likelihood of experiencing the Ames window illusion. This prompts an interesting follow-up question: What are the relative strengths of solidity and competing cues? Future research can address this question by, for example, employing quantitative psychophysics measures and systematically varying the strength of solidity (e.g., by varying the width of the bar or the ruler) and competing cues.

Our findings raise some other intriguing questions. Is solidity innately embedded in the visual system as a product of evolution, or is it learned solely through experience? Future research could investigate how preverbal infants or even neonates perceive the motion displays tested in the present study to address this question. Furthermore, given the universality of the solidity constraint in our world, does the assumption for solidity also exist in other species' perceptual systems? Research has shown that non-human primates fail at using the solidity constraint to represent the position of a hidden object^{54,55} when they are given tasks similar to infant reasoning studies, leaving open the question of whether solidity is integrated in their visual mechanisms, especially in light of existing data showing that non-human primates experience dynamic multistable stimuli in a way similar to humans^{56–58}.

Methods

Participants

All participants ($N = 1167$) were adult humans, recruited online on Prolific. They all gave consent prior to participation and received compensation upon completion of the experiment. This research complied with all ethical regulations of and was approved by CERES. The study adhered to the Declaration of Helsinki principles and guidelines. Each participant only took part in one of the experiments.

Stimuli and Procedure

The trial structure of all five experiments was created with the JavaScript framework JsPsych⁵⁹. The stimuli were created with JavaScript on Canvas. The response options were photorealistic animations and were first rendered with Blender 2.82 (<https://www.blender.org/>) then displayed on JavaScript's Canvas.

All five experiments were intended to be as similar as possible. At the beginning of each trial, a mask consisting of noise patches was shown for 1.5 seconds. The test stimuli, along with a fixation cross at its center (of a color different from the test stimuli; with the exception that trials in Experiment 2 did not have a fixation cross) then appeared at the center of the screen. Participants were instructed to stare at the fixation cross while attending to the stimuli. 4 seconds after the stimuli appeared, the response options were shown and participants clicked on the option that best depicted the stimuli's motion (with the exception that there were no options in Experiment 2). All the animations were looping and the trials advanced once a response was recorded.

Experiment 1

The test stimuli consisted of two animated 2D circles whose width expanded and shrunk following a sinusoidal function relative to time with an angular speed of $\pi/50$ per frame (Figure 1A). This pattern of motion leads to a percept of three-dimensional circles rotating in depth. In each trial, one response option showed two rings moving in 180° co-rotations, bouncing back when they reached the fronto-parallel plane. The other response option illustrated two rings moving in 360° co-rotations continuously towards the same direction. For each participant, the 360° and 180° options always appeared at the same positions throughout the experiment (e.g. 360° always on the left, 180° always on the right). Both 360° and 180° options had two versions (moving clockwise and counterclockwise), which were counterbalanced across trials. Notice that under this design, the rate of 180° responses are unlikely to reach 100%, because the interpretation that participants see might not be available (e.g., if participants see 360° clockwise co-rotation, but only 360° counterclockwise co-rotation is an available option, they might opt for the 180° option). While counter-rotations are also possible interpretations of the stimuli, such options were not

shown because existing studies have demonstrated that when multistable stimuli are presented close to each other, the visual system tends to apply the same interpretation to all stimuli^{60,61}.

Participants were divided into 2 independent groups. One group received “overlap” and “separated” conditions, the other received “gapped” and “separated” conditions. For the “gapped” conditions, the gaps appeared on the ring on the right, while the other ring was full. As our pilot data did not show any difference between gaps on the right vs. on the left, we did not counter-balance the gap position. Each participant saw 10 trials, 5 of each condition, randomly distributed across the experiment. The colors of the ambiguous rings are varied across trials so that participants do not repeatedly receive identical stimuli.

Experiment 2

The rings were identical to those of Experiment 1 except that they were made slightly thicker. A horizontal line was added to the right hand side of the rings. The length of the line could be adjusted by pressing the left and right arrows on the keyboard.

The ring configuration (overlap and separated), size (small, medium and large) and color were varied across trials. All participants received 48 trials, including all trial types.

Experiment 3

The test stimuli were identical to those of Experiment 1, except that shadows were added below them. We created the photorealistic shadows in Blender 2.82 by first creating a pair of rotating 3D rings (the same ones used in response options) with a stationary overhead surface lighting and a horizontal surface underneath. We then output these rings’ shadows casted upon the surface (automatically generated by Blender) as frames. These frames were then processed in R to be transformed into grayscale images, then adjusted to match the desired contrast levels. Contrast levels were calculated using root mean square (RMS). The contrast levels of 0.20, 0.10 and 0.05 were the mean RMS contrast of all frames of a display. In the control condition (i.e., no shadow), the frames were a homogenous gray image. The response options were identical to those from Experiment 1, except that shadows were removed.

Participants were divided into three groups. Each participant received 24 trials, which include two spatial configurations (overlapping and separated rings), three shadow types (360° rotation, 180° rotation and no shadows), and one level of contrast.

Experiment 4

The test stimuli were an untextured circle oscillating in a horizontal path. Its speed followed a sinusoidal function relative to time with an angular speed of $\pi/50$ per frame. An untextured rectangle (i.e., a bar) in the same color as the circle was either positioned along the perpendicular bisector of the circle’s path, or was away from the path. The response options consisted of a ball and a vertical bar in 3D. One option

showed a ball moving circularly in depth, the other showed a ball moving along a horizontal linear path in the fronto-parallel plane. For each participant, the circular and linear options always appear at the same positions throughout the experiment (e.g. circular always on the left, linear always on the right).

Each participant saw 12 trials. In 6 of them, the circle and bar were separated while in the other 6 trials, they were overlapping. The two types of trials were randomly distributed across the experiment. The colors of the circle and the rectangle were varied across trials.

Experiment 5

Trials were identical to Experiment 4 with the exception that size changes were introduced to the circle. There were three size change levels: 0, 3% and 6%. These numbers refer to the amount of increase and decrease in diameter when the circle was at the center compared to when it was at the two extremities (see Figure 2C). The diameter change followed a sinusoidal function of time, so the diameter at a given moment d_t was $d_t = d + \sin(t) \cdot d \cdot \mu$ (where μ is the size change level, d is the diameter at the extremities, identical to that in Experiment 4). The circle and the bar were either overlapping or separated. We also added a filler condition, where the bar had a color different from the circle and overlapped with the circle's path (like in the overlap condition). The bar alternated between being in front of and behind the circle each time the circle reached it (as if the circle was circling around the bar in depth). The purpose of this condition was to (1) balance the amount of "circular" responses, given that otherwise participants might click on the "linear" response most of the time, and (2) give a rough estimate of the ceiling of "circular" responses.

Each participant received 54 trials, including all three size change levels, two conditions (overlap and separated) as well as the filler condition. When size change was not 0, it was counterbalanced between clockwise and counterclockwise rotations (viewed from above). The size changes (and occlusion patterns for the filler condition) were always in line with the circular option's rotation direction. For instance, if the circular option was rotating counterclockwise, then the circle would increase then decrease in size as it moved from left to right, and decrease then increase in size as it moved from right to left. When the bar was separated from the circle, the position of the bar was counterbalanced (lefthand or righthand side). All types of trials were randomly distributed across the experiment.

Data Analysis

The planned analyses, exclusion criteria and sample size were pre-registered prior to data collection for all five experiments. A pilot had been carried out prior to each of these experiments and the sample size was calculated with R based on the pilot data, with a power of .80 (0.95 for Experiment 2, due to the low required sample size) and α of .05. The required sample sizes for experiment 1-5 were respectively 400, 80, 191, 139 and 100 in total after exclusion. We recruited 505, 89, 267, 163 and 143 participants before exclusion, and 404, 85, 202, 140 and 115 after exclusion. The exclusion criteria were planned in

pre-registration and were the following. First, three attention questions were included at the end of the experiments and participants failing to correctly answer any of them were rejected. Second, participants who did not respond “Yes” to the feedback question “Are the videos displayed smoothly?” were rejected. Three, in each condition, responses with a reaction time that lied outside Median \pm 3 Median Absolute Deviation (MAD) were rejected, with the exception that Experiment 2 rejected responses with a length outside of Mean \pm 3 SDs. For Experiments 2, 4 and 5, another debrief question was added asking participants to rate how much they were able to stay focused through the experiment (from 1 to 100). Participants giving a response below 60 were rejected. The pre-registration documents are available on Open Science Framework (OSF): <https://osf.io/k97v4/> (Experiment 1), <https://osf.io/a28z3> (Experiment 2), <https://osf.io/7ar3x> (Experiment 3), <https://osf.io/s3gru> (Experiment 4) and <https://osf.io/9h3x7> (Experiment 5).

All analyses followed those planned in the pre-registrations, with the exception of Experiment 3. In this experiment, we found the predicted effects for all the planned analyses. However, upon careful consideration, we opted to not include some of them, as they were actually not crucial to the point we try to make. Instead, we reported some analyses that were not planned that we deemed as important: “overlap” vs. “separated” with shadows, 360° shadow vs. control, 180° shadow vs. control, “overlap” vs. “separated” with 360° shadows, “overlap” vs. “separated” with 180° shadows. The *p*-values for these analyses were all below 0.0001, indicating that it is highly unlikely that they were due to fluctuations.

Data and code availability

All data analyses were performed on R. The pre-registration, raw data, R scripts for data filtering and statistical analyses are all available on Open Science Framework: <https://osf.io/6pjyq/> (Experiment 1), <https://osf.io/dw468/> (Experiment 2), <https://osf.io/68cfk/> (Experiment 3), <https://osf.io/hk85n/> (Experiment 4), <https://osf.io/c6rs7/> (Experiment 5).

References

1. Battaglia, P. W., Hamrick, J. B. & Tenenbaum, J. B. Simulation as an engine of physical scene understanding. *Proc. Natl. Acad. Sci.* **110**, 18327–18332 (2013).
2. Fischer, J., Mikhael, J. G., Tenenbaum, J. B. & Kanwisher, N. Functional neuroanatomy of intuitive physical inference. *Proc. Natl. Acad. Sci.* **113**, E5072–E5081 (2016).
3. Firestone, C. & Keil, F. C. Seeing the tipping point: Balance perception and visual shape. *J. Exp. Psychol. Gen.* **145**, 872–881 (2016).
4. López-Moliner, J., Brenner, E., Louw, S. & Smeets, J. B. J. Catching a gently thrown ball. *Exp. Brain Res.* **206**, 409–417 (2010).
5. Zago, M., McIntyre, J., Senot, P. & Lacquaniti, F. Visuo-motor coordination and internal models for object interception. *Exp. Brain Res.* **192**, 571–604 (2009).
6. Ullman, T. D., Spelke, E., Battaglia, P. & Tenenbaum, J. B. Mind Games: Game Engines as an Architecture for Intuitive Physics. *Trends Cogn. Sci.* **21**, 649–665 (2017).
7. Shepard, R. N. Perceptual-cognitive universals as reflections of the world. *Behav. BRAIN Sci.* **21** (2001).
8. de Lange, F. P., Heilbron, M. & Kok, P. How Do Expectations Shape Perception? *Trends Cogn. Sci.* **22**, 764–779 (2018).
9. Helmholtz, H. von. *Treatise on Physiological Optics*. (Courier Corporation, 2013).
10. Shepard, R. N. Ecological constraints on internal representation: Resonant kinematics of perceiving, imagining, thinking, and dreaming. *Psychol. Rev.* **91**, 417–447 (1984).
11. Kominsky, J. F. *et al.* Categories and Constraints in Causal Perception. *Psychol. Sci.* **28**, 1649–1662 (2017).
12. Yang, Y.-H. & Wolfe, J. M. Is apparent instability a guiding feature in visual search? *Vis. Cogn.* **28**, 218–238 (2020).
13. Scholl, B. J. & Pylyshyn, Z. W. Tracking Multiple Items Through Occlusion: Clues to Visual Objecthood. *Cognit. Psychol.* **38**, 259–290 (1999).
14. Baillargeon, R. Object Permanence in 3 1/2- and 4 1/2-Month-Old Infants. *Dev. Psychol.* **23**, 655–

- 664 (1987).
15. Baillargeon, R., Spelke, E. S. & Wasserman, S. Object permanence in five-month-old infants. *Cognition* **20**, 191–208 (1985).
 16. Spelke, E. S., Breinlinger, K., Macomber, J. & Jacobson, K. Origins of knowledge. *Psychol. Rev.* **99**, 605–632 (1992).
 17. Baillargeon, R. & DeVos, J. Object Permanence in Young Infants: Further Evidence. *Child Dev.* **62**, 1227–1246 (1991).
 18. Lin, Y., Stavans, M. & Baillargeon, R. Infants' Physical Reasoning and the Cognitive Architecture that Supports It. in *The Cambridge Handbook of Cognitive Development* (eds. Houdé, O. & Borst, G.) 168–194 (Cambridge University Press, 2022).
doi:10.1017/9781108399838.012.
 19. Shiffrar, M. & Freyd, J. J. Apparent Motion of the Human Body. *Psychol. Sci.* **1**, 257–264 (1990).
 20. Kim, S.-H., Feldman, J. & Singh, M. Curved apparent motion induced by amodal completion. *Atten. Percept. Psychophys.* **74**, 350–364 (2012).
 21. Berbaum, K. & Lenel, J. C. Objects in the Path of Apparent Motion. *Am. J. Psychol.* **96**, 491–501 (1983).
 22. Rolfs, M., Dambacher, M. & Cavanagh, P. Visual Adaptation of the Perception of Causality. *Curr. Biol.* **23**, 250–254 (2013).
 23. Michotte, A. *The Perception of Causality*. (Routledge, 2017). doi:10.4324/9781315519050.
 24. Gilroy, L. A. & Blake, R. Physics embedded in visual perception of three-dimensional shape from motion. *Nat. Neurosci.* **7**, 921–922 (2004).
 25. Bai, D. & Strickland, B. The Pulfrich solidity illusion: a surprising demonstration of the visual system's tolerance of solidity violations. *Psychon. Bull. Rev.* (2023) doi:10.3758/s13423-023-02271-9.
 26. Pulfrich, C. Die Stereoskopie im Dienste der isochromen und heterochromen Photometrie. *Naturwissenschaften* **10**, 751–761 (1922).
 27. Burge, J., Rodriguez-Lopez, V. & Dorronsoro, C. Monovision and the Misperception of Motion. *Curr. Biol.* **29**, 2586-2592.e4 (2019).

28. Lit, A. The Magnitude of the Pulfrich Stereophenomenon as a Function of Binocular Differences of Intensity at Various Levels of Illumination. *Am. J. Psychol.* **62**, 159–181 (1949).
29. Morgan, M. J. Pulfrich effect and the filling in of apparent motion. *Perception* **5**, 187–195 (1976).
30. Morgan, M. J. & Thompson, P. Apparent Motion and the Pulfrich Effect. *Perception* **4**, 3–18 (1975).
31. Rogers, B. J. & Anstis, S. M. Intensity versus adaptation and the Pulfrich stereophenomenon. *Vision Res.* **12**, 909–928 (1972).
32. Wilson, J. A. & Robinson, J. O. The Impossibly Twisted Pulfrich Pendulum. *Perception* **15**, 503–504 (1986).
33. Leslie, A. M. The necessity of illusion: Perception and thought in infancy. in *Thought without language* 185–210 (Clarendon Press/Oxford University Press, 1988).
34. Ames Jr., A. Visual perception and the rotating trapezoidal window. *Psychol. Monogr. Gen. Appl.* **65**, i–32 (1951).
35. Katsuyama, N., Usui, N., Nose, I. & Taira, M. Perception of object motion in three-dimensional space induced by cast shadows. *NeuroImage* **54**, 485–494 (2011).
36. Kersten, D., Knill, D. C., Mamassian, P. & Bülthoff, I. Illusory motion from shadows. *Nature* **379**, 31–31 (1996).
37. Kersten, D., Mamassian, P. & Knill, D. C. Moving cast shadows induce apparent motion in depth. *Perception* **26**, 171–192 (1997).
38. Regan, D. & Beverley, K. I. Looming detectors in the human visual pathway. *Vision Res.* **18**, 415–421 (1978).
39. Regan, D., Erkelens, C. J. & Collewyn, H. Necessary conditions for the perception of motion in depth. *Invest. Ophthalmol. Vis. Sci.* **27**, 584–597 (1986).
40. Regan, D. & Beverley, K. I. Binocular and monocular stimuli for motion in depth: Changing-disparity and changing-size feed the same motion-in-depth stage. *Vision Res.* **19**, 1331–1342 (1979).
41. Cheries, E. W., Mitroff, S. R., Wynn, K. & Scholl, B. J. Do the same principles constrain persisting object representations in infant cognition and adult perception?: The cases of continuity

- and cohesion. in *The Origins of Object Knowledge* (eds. Hood, B. M. & Santos, L. R.) 0 (Oxford University Press, 2009). doi:10.1093/acprof:oso/9780199216895.003.0005.
42. Leslie, A. M., Xu, F., Tremoulet, P. D. & Scholl, B. J. Indexing and the object concept: developing 'what' and 'where' systems. *Trends Cogn. Sci.* **2**, 10–18 (1998).
 43. Carey, S. & Xu, F. Infants' knowledge of objects: beyond object files and object tracking. (2001).
 44. Needham, A. The role of shape in 4-month-old infants' object segregation. *Infant Behav. Dev.* **22**, 161–178 (1999).
 45. Cheries, E. W., Mitroff, S. R., Wynn, K. & Scholl, B. J. Cohesion as a constraint on object persistence in infancy. *Dev. Sci.* **11**, 427–432 (2008).
 46. Huntley-Fenner, G., Carey, S. & Solimando, A. Objects are individuals but stuff doesn't count: perceived rigidity and cohesiveness influence infants' representations of small groups of discrete entities. *Cognition* **85**, 203–221 (2002).
 47. Leslie, A. M. The Perception of Causality in Infants. *Perception* **11**, 173–186 (1982).
 48. Kotovsky, L. & Baillargeon, R. The development of calibration-based reasoning about collision events in young infants. *Cognition* **67**, 311–351 (1998).
 49. Teichmann, L., Edwards, G. & Baker, C. I. Resolving visual motion through perceptual gaps. *Trends Cogn. Sci.* **25**, 978–991 (2021).
 50. Erlikhman, G. & Caplovitz, G. P. Decoding information about dynamically occluded objects in visual cortex. *NeuroImage* **146**, 778–788 (2017).
 51. Mitroff, S. R., Scholl, B. J. & Wynn, K. Divide and Conquer: How Object Files Adapt When a Persisting Object Splits Into Two. *Psychol. Sci.* **15**, 420–425 (2004).
 52. Kominsky, J. F. & Scholl, B. J. Retinotopic adaptation reveals distinct categories of causal perception. *Cognition* **203**, 104339 (2020).
 53. Scholl, B. J. & Tremoulet, P. D. Perceptual causality and animacy. *Trends Cogn. Sci.* **4**, 299–310 (2000).
 54. Santos, L. R. 'Core Knowledges': a dissociation between spatiotemporal knowledge and contact-mechanics in a non-human primate? *Dev. Sci.* **7**, 167–174 (2004).
 55. Hauser, M. D. Searching for food in the wild: a nonhuman primate's expectations about invisible

- displacement. *Dev. Sci.* **4**, 84–93 (2001).
56. Grunewald, A., Bradley, D. C. & Andersen, R. A. Neural Correlates of Structure-from-Motion Perception in Macaque V1 and MT. *J. Neurosci.* **22**, 6195–6207 (2002).
57. Dodd, J. V., Krug, K., Cumming, B. G. & Parker, A. J. Perceptually Bistable Three-Dimensional Figures Evoke High Choice Probabilities in Cortical Area MT. *J. Neurosci.* **21**, 4809–4821 (2001).
58. Carter, O., van Swinderen, B., Leopold, D. A., Collin, S. & Maier, A. Perceptual rivalry across animal species. *J. Comp. Neurol.* **528**, 3123–3133 (2020).
59. de Leeuw, J. R. jsPsych: A JavaScript library for creating behavioral experiments in a Web browser. *Behav. Res. Methods* **47**, 1–12 (2015).
60. Eby, D. W., Loomis, J. M. & Solomon, E. M. Perceptual linkage of multiple objects rotating in depth. *Perception* **18**, 427–444 (1989).
61. Ramachandran, V. S. & Anstis, S. M. Perceptual organization in moving patterns. *Nature* **304**, 529–531 (1983).