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BRIEF REPORT

The Pulfrich solidity illusion: a surprising demonstration of the visual system's tolerance of solidity violations

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Abstract
Physical objects behave following the principle of solidity: One solid object cannot pass through another. To what extent does the visual system integrate this physical regularity as a prior constraint? A new variant of the Pulfrich effect demonstrates a surprising degree of tolerance for violations of solidity when pitted against motion and depth cues. When adult participants view a pendulum swinging in the fronto-parallel plane with both eyes (one of which was covered by a light-attenuating filter), they falsely perceive the pendulum as swinging in an elliptical path (known as the "Pulfrich effect"). Here, we show that even when the pendulum's motion takes place entirely behind a solid horizontal bar, observers nevertheless see the pendulum pass through the bar while moving in an ellipse. This illusion suggests that the Pulfrich effect and the underlying stereoscopic depth cues can be robust to object solidity.

Keywords Solidity · High-level perception · Visual illusion · Pulfrich effect · Depth perception

Introduction

Objects in our world exist, behave and interact with each other following certain physical regularities and constraints. The human visual system integrates some of these regularities as prior expectations (De Lange et al., 2018; Shepard, 2001; Ullman et al., 2017). To name a few examples, object permanence underlies multiple object tracking: When visually tracking multiple objects, observers' performance is not impacted if the targets undergo occasional occlusion, suggesting that the visual system is endowed with expectation that objects should continue to exist while occluded (Scholl & Pylyshyn, 1999). Object stability guides visual attention: It is easier to find an unstable vase among stable ones than vice versa, suggesting that the visual system computes object stability (Yang & Wolfe, 2020). Newtonian laws also guide attention in the context of two-object collisions: Speed patterns violating Newtonian laws are more easily detected than speed patterns respecting them, suggesting that the visual system recognizes violations of Newtonian laws (Kominsky et al., 2017). Put succinctly, our visual system embeds prior expectations about certain aspects of the normal behavior of physical objects and uses these priors to guide attention and shape perception.

The present study investigates to what extent the principle of object solidity (i.e., that one solid object cannot pass through another) is used by the visual system to compute object motion. It is well established from studies in developmental psychology that preverbal infants as young as 2.5 months old readily expect objects to behave following the solidity constraint (Baillargeon, 1987; Hespos & Baillargeon, 2001; Spelke et al., 1992). This suggests a deeply ingrained expectation that objects will obey the solidity principle. For instance, Spelke et al. (1992) investigated the representation of solidity in 2.5-month-olds with a habituation paradigm. After being habituated to the stimuli, infants were shown a ball rolling behind an occluder. When the occluder was removed, infants looked longer if the ball reappeared in front of a solid barrier than if it reappeared behind it (which required the ball to previously traverse the barrier). These results suggest that infants expect the ball to be impeded by the barrier, following the principle of object solidity. However, it is unclear whether such performance reflects infants'

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expectations in higher-level cognition (e.g., reasoning) or lower-level vision. That is, it remains an open question as to whether the infants achieved the expectations for solidity through some form of *cognitive* process like reasoning (in a similar way that you calculate the sum of 11 and 8, or decide which stock to buy), or *visual* process (in a similar way that your visual system computes orientation or depth).

Clear evidence that solidity does guide visual perception is scant. One of the strongest pieces of positive evidence comes from the classic Shiffrar and Freyd (1990) study. Participants were shown apparent motion displays consisting of two alternating photographs of a human body, with one body part in two different positions (e.g., an arm in front of and behind the torso). Crucially, the shortest possible path that the body part could take required it to pass through another body part, thus violating solidity. The data revealed that under certain stimulus onset asynchronies, observers did not report perceiving the body part moving in the shortest path (as is typical in apparent motion paradigms), but instead they reported seeing physically possible and longer paths. The authors interpreted these results as demonstrating that the visual system takes into account solidity constraints when generating apparent motion. However, similarly to the findings in infants, this interpretation is open to debate as it is possible that participants' reports reflected cognitive processes (as opposed to visual processes): Participants may have given the physically plausible response because they *reasoned* that such response was appropriate, instead of truly *perceiving* the effect.

In addition to a general lack of clear evidence for solidity in vision, an old visual illusion demonstrates that the visual system may actually be tolerant to obvious violations of solidity under specific conditions. This illusion is a variation of the famous Ames window illusion (Ames, 1951). In the Ames window illusion, when observers look at a rotating trapezoidal window, they falsely perceive the window moving in oscillation. Remarkably, if a ruler is fixed perpendicularly through the window in a way that they rotate together, observers correctly perceive the rotating ruler, while the window still appears to oscillate back and forth. As a consequence, observers occasionally perceive the ruler pass through the window, creating an illusory solidity violation. This visual illusion demonstrates that the solidity constraint can be overridden by perspectival depth cues when they are put in competition.

In the present study, we examined to what extent the visual system employs prior expectation of solidity to compute object motion. We report below a new variant of the Pulfrich effect—the Pulfrich solidity illusion—in which an obvious solidity violation occurs. This example provides novel evidence that when the solidity constraint is put in competition with stereoscopic-motion-based depth cues, solidity can be ignored even when its use would lead to an objectively correct motion percept.

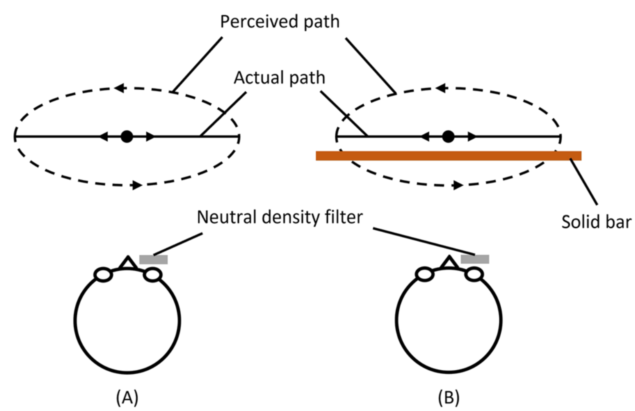

Fig. 1 Original Pulfrich effect (**A**) and our version (**B**). In (**A**), the observer wears a neutral-density filter on one eye and perceives the pendulum moving in an elliptical path in depth (dotted line), while the actual path is in the fronto-parallel plane (solid line). In (**B**), a horizontal bar is placed in front of the pendulum so that it cuts through the pendulum's illusory path

We created this illusion in the context of the well-known Pulfrich effect, first reported a century ago. In the original Pulfrich effect, a pendulum oscillating in the fronto-parallel plane appears to move in an ellipse in depth when viewed with both eyes, one of which is covered by a neutral-density filter (i.e., a filter that reduces the amount of light passing through; Pulfrich, 1922; Fig. 1A). It is generally accepted that this illusion is created because darker images are processed more slowly in the visual system, and the subsequent delay between the two eyes' images leads to a perceived stereoscopic depth that is in front of or behind the actual depth—depending on towards which direction the pendulum is swinging—hence the perceived elliptical path (Burge et al., 2019; Lages et al., 2003; Lit, 1949; Morgan, 1976; Morgan & Thompson, 1975; Reynaud & Hess, 2017; Rogers & Anstis, 1972).

We asked whether a potential violation of solidity would alter the illusory percept in the Pulfrich effect. Specifically, we modified the original setup by placing a solid bar horizontally in front of the pendulum, in such a way that the bar cuts through the illusory trajectory (Fig. 1B). In this situation, the visual system is faced with a conundrum that it could theoretically solve in one of the two ways. The first possibility is that it allows for a violation of the solidity constraint while keeping the time-lagged images of the pendulum when computing stereoscopic depth. In this case, observers would perceive the pendulum's string traversing the bar in an elliptical path as in the classic Pulfrich effect. The alternative possibility is that the visual system respects the solidity principle, thus temporally realigning the two images it fuses and replacing the perceived elliptical motion with the actual motion. In this case, we would perceive the pendulum swinging in the

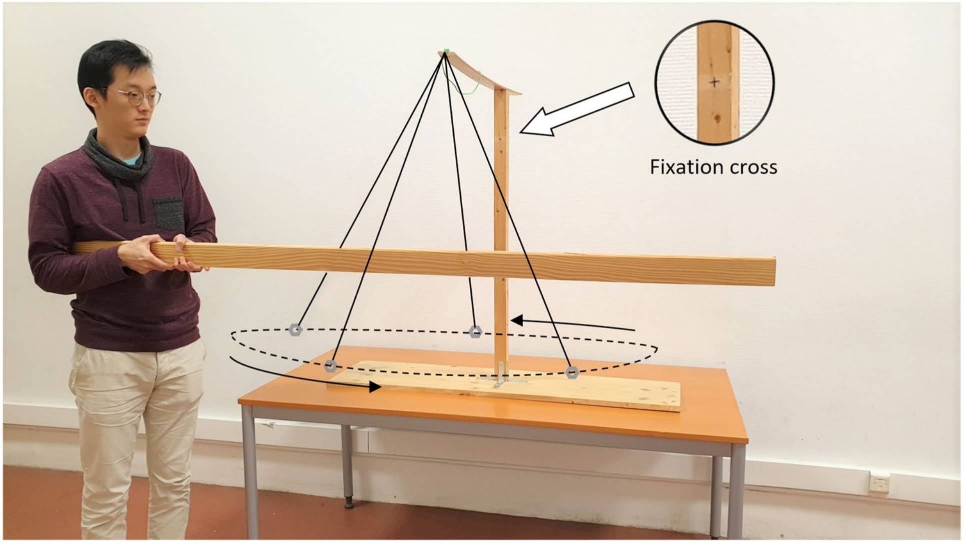

Fig. 2 Experimental setup and a schematic illustration of the perceived illusion. Participants were instructed to stare at the fixation cross on the central column and attend globally to the scene. In reality, the pendulum's motion (not depicted) took place entirely behind the horizontal bar. However, the pendulum (i.e., the nut and the string) appeared to swing in an elliptical path. The bar shown is the thick wooden bar. The photo was not taken from the participants' point of view

fronto-parallel plane entirely behind the bar. Which option our visual system takes depends on the relative priority it assigns to solidity versus stereoscopic cues of depth in the context of Pulfrich effect. This design is inspired by Wilson and Robinson's (1986; see also Leslie, 1988) double pendulum illusion, where two rigid pendula swinging in opposite directions and in parallel planes (one plane slightly behind the other) appear to run through each other when viewed through a neutral-density filter like in the classic Pulfrich setting. Our design offers a more direct demonstration of perceived solidity violations.

To foreshadow our results, described in more detail below, the visual system robustly opts for the first theoretical possibility: The pendulum appears to move in an ellipse and traverse the bar. We first demonstrated this illusion at the 2015 Annual Meeting of the Vision Science Society (VSS) demo night to roughly 200 people. The majority of participants reported experiencing the illusion. Those who did not experience the illusion also claimed to have preexisting problems with vision (e.g., stereoscopic vision).

We also conducted a laboratory experiment. Traditionally, visual illusions do not require experiments, because readers can usually experience the illusion themselves when viewing static images. Given the dynamic nature of the illusion, and the fact that it requires actual presence in front of a physical apparatus, that strategy is unfortunately not possible here. Therefore, the goal of this experiment was to simply provide formal evidence confirming that observers do actually experience the illusion.

Method

Participants

Forty adults (mean age = 25.2 years, 12 females) were recruited. As this experiment was run in 2015, it fell under the framework of noninvasive psychological research and was thus exempted from the need for further approval from the local (CERES) ethical committee. All participants gave informed consent using a standardized consent form for studies of this type, and the study adhered to the Declaration of Helsinki principles and guidelines. Participants were not remunerated for their participation and were naïve to the purpose of the experiment. They did not undergo any visual tests but confirmed having good (or corrected) eyesight and no neurological issues.

Stimuli

A pendulum was constructed to test the illusion. A hexagonal metal nut was suspended from the top of the pendulum structure through a one-meter string (subtending approximately 9.37° of visual angle from the position of the participants), allowing the nut to swing like a pendulum bob (Fig. 2). A fixation cross of 2 cm × 2 cm (~0.19° of visual angle) was drawn on the central column of the structure, 16 cm (~1.50°) from the center of the pendulum's motion. The pendulum was set on a table such that the nut was 80 cm above the floor (~7.29°). Three types of bars were used to be placed horizontally in front of the pendulum: A thin wooden bar (width = 4.6 cm, ~0.43°), a thick wooden bar (width = 7.6 cm, ~0.71°; Fig. 2), and a metal bar (width = 3.5 cm, ~0.33°). All three bars were longer than 160 cm (~16.00°) to ensure that when they were held horizontally by an experimenter, the swinging pendulum's string was always partially occluded during the experiment from the participants' point of view.

Procedure

The experiment took place in a room with overhead lighting. Participants stood 6.1 meters in front of the pendulum's swinging plane. They were instructed to look in the direction of the fixation cross on the central column of the pendulum and attend globally to the scene. They looked with both eyes, one of which was covered by a neutral-density filter. Participants with glasses wore the filter over their glasses. They were divided into three test groups and one control group. In the test groups, placed in front of the pendulum was the thin wooden bar, the thick wooden bar, or the metal bar. Participants in the control group performed the task with the thin wooden bar but without the neutral-density filter. Respectively 10, 11, 10, and nine participants received the "thin wood," "thick wood," "metal," and control conditions, respectively.

One experimenter set the pendulum's bob in motion such that it swung in the participants' fronto-parallel plane (if the pendulum bob slowed down over time, the experimenter reset the bob in motion). The two extremities of the bob's path were approximately 7.97° of visual angle from the fixation cross. Then the experimenter held one of the bars horizontally, 5 cm in front of the swinging pendulum, 55 cm (~5.15°) below the top of the pendulum structure. While the participants were looking at the pendulum, they were questioned by a second experimenter about what they were seeing and wrote down the responses. Two questions were crucial, whereas six other questions were fillers intended to cover the purpose of the questionnaire. The first crucial question (posed as the fifth question) asked the subjects to freely describe the relationship between the string and the bar. Importantly, the experimenters made no mention of a potential solidity violation prior to this crucial question. The second crucial question (posed as the sixth question) asked to what extent they had the impression that the string passed through the bar (on a scale from 0 to 7, 0 = *not at all* to 7 = *every time, very clearly*). The full list of questions can be found in supplementary material.

A photorealistic animation of the experimental setup has also been rendered using Blender 2.82 (https://www.blender.org/). All the physical properties in the virtual display such as objects' size, texture, color and position were set to be as close as possible to the real-world experiment. The animation is accessible online (https://osf.io/uwynv/). The purpose of the animation is to demonstrate the experimental setting, rather than to allow viewers to perceive the illusion on screen. This said, if the viewing conditions are ideally set up (as instructed in the video), some viewers have reported being able to experience the illusion—although in a much less spontaneous manner than in the real-life experiment.

Results

We focused our analyses on the two crucial questions. The responses to the question asking participants to freely describe the relationship between the string and the bar were transformed by an experimenter into a binary variable of "mention": Any statement referring to the string apparently passing through the bar was counted as "mention." Respectively, 40%, 45.5%, 40%, and 0% of participants in thin wood, thick wood, metal, and control conditions mentioned that the string passed through the bar (Fig. 3A), and notably did so in a *spontaneous* manner. With regard to this binary variable of mention, chi-squared tests revealed that the each of the three test conditions were significantly different from the control condition: Thin wood vs. control, $\chi^2(1) = 4.56$, $p = .033$, $d = 1.12$, 95% CI [0.09, 2.16], thick wood vs. control, $\chi^2(1) = 5.45$, $p = .020$, $d = 1.22$, 95% CI [0.20, 2.25], and metal vs. control, $\chi^2(1) = 4.56$, $p = .033$, $d = 1.12$, 95% CI [0.09, 2.16]. For the rating question on the extent to which participants had the impression that the string passed through the bar, we first checked the data's normality with the Shapiro–Wilk normality test. The distributions for thin wood ($W = 0.910$, $p = .284$) and metal ($W = 0.932$, $p = .466$) were not significantly different from a normal distribution. Thick wood ($W = 0.811$, $p = .013$) and control conditions ($W = 0.531$, $p < .001$) yielded significance, which could be explained by the low sample size and the fact that in the control condition, seven participants responded "0," one responded "2," and one responded "6." We therefore assumed that the data followed a normal distribution. The ratings were on average 4.65 ($SD = 1.94$), 5.27 ($SD = 2.15$), 5.30 ($SD = 1.34$), and 0.89 ($SD = 2.03$), respectively in thin wood, thick wood, metal, and control conditions (Fig. 3B). Importantly, no participant in the three test conditions responded 0 (*not at all*), while in the control condition, seven out of nine participants responded 0. A one-way ANOVA showed no significant difference in ratings between the three test conditions, $F(2, 28) = 0.399$, $p = .675$, $\eta^2 = 0.03$. Unpaired t tests showed that the ratings for all test conditions were higher than the control condition: Thin wood vs. control, $t(16.61) = 4.12$, $p < .001$, $d = 1.90$, 95% CI [0.73, 3.06], thick wood vs. control, $t(17.58) = 4.68$, $p < .001$, $d = 2.09$, 95% CI [0.92, 3.26], and metal vs. control, $t(13.63) = 5.53$, $p < .0001$, $d = 2.60$, 95% CI

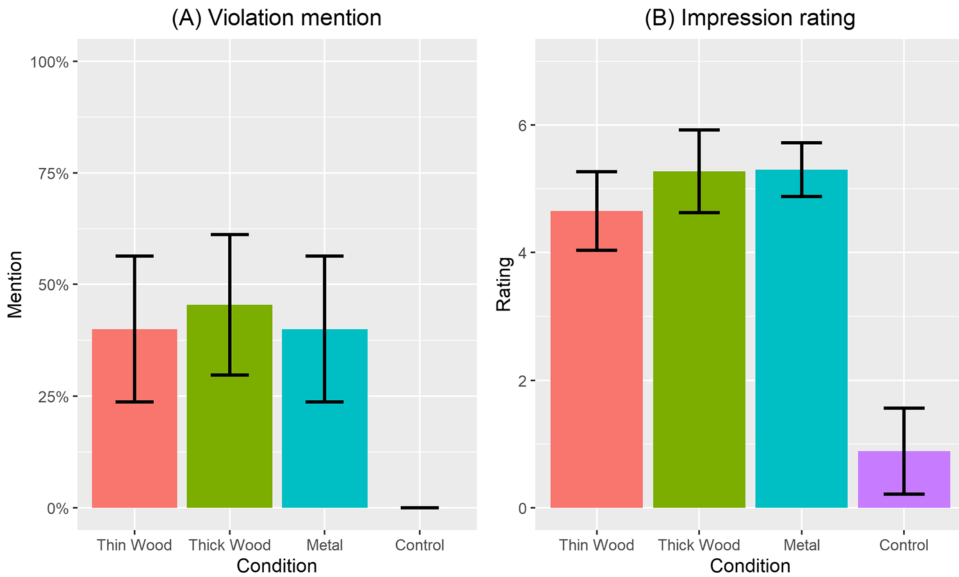

Fig. 3 Results summary. **A** Percentage of participants mentioning that the pendulum traversed the bar in the open question. **B** Ratings of the impression that the pendulum traversed the bar. Error bars depict standard errors

[1.28, 3.91]. Participants who mentioned solidity violations scored on average 5.85 (SD = 1.07) for the rating question (all three test conditions collapsed, excluding control condition), significantly higher than those who did not mention violation (M = 4.53, SD = 2.06), shown by unpaired t test, $t(26.75) = 2.32$, $p = .028$, $d = 0.77$, 95% CI [−0.005, 1.54].

Thus, participants looking through a neutral-density filter perceived the string pass through the bars (as is depicted in Fig. 2). Participants without the filter did not experience this illusion. All the raw data are available on Open Science Framework (https://osf.io/3dtmq/).

Discussion

The present illusion demonstrates a surprising degree of tolerance for violations of the basic physical law of solidity: The visual system accepts violations of solidity in the context of the Pulfrich effect. Instead of incorporating prior information (i.e., pertaining to the solidity principle) that can help to compute the correct trajectory, the visual system more readily uses the stereoscopic depth cues at the expense of accepting violations of solidity. Importantly, the neglect of the solidity principle in this case leads observers to a percept that is at odds with explicit background knowledge. That is, despite knowing at the cognitive level that the pendulum's string should not traverse the bar, one still perceives the event as such. Therefore, unlike previous studies that leave open the question about whether the mechanisms involved are visual or cognitive, our data reflect a visual process, as opposed to a higher-level cognitive process.

What is the strength of the solidity prior in the human mind? Despite being an inviolable principle of our daily physical world, object solidity is not processed as an inviolable prior. In addition to the present illusion, the variant of the Ames window illusion (Ames, 1951) offers a similar case of perspectival depth cues being robust to solidity and leading to a perceived solidity violation. These illusions suggest that solidity representation may not be robust in the computations of object motion and depth. More recent experimental research also provides evidence along the same lines. For example, Falck et al. (2020) asked adult human participants to detect the appearing location of a target that occasionally underwent violations of spatiotemporal continuity (i.e., objects teleported from one location to another) or violations of solidity. Participants detected the target more accurately and faster in events involving solidity violations than for those involving continuity violations, suggesting a weaker prior for solidity than for continuity. Furthermore, despite displaying sensitivity to solidity violations in studies measuring looking time (with the method of habituation; Baillargeon et al., 1985), infants as old as 2 years fail to behave in accordance to solidity when they perform a manual task. Thus, after viewing an object being dropped behind an occluder where a table stands, they manually searched for it below the table surface, neglecting the solidity constraint (in another design, after viewing a ball rolling down a slide and supposedly stopping at a barrier behind an occluder, infants searched beyond the barrier; Berthier et al., 2000; Hood et al., 2000, 2003). The same pattern of results was obtained with nonhuman primates (Hauser, 2001; Santos, 2004): With similar stimuli, adult rhesus macaques also searched at the location requiring solidity violation. Taken together, the solidity principle, while present from an early age, may receive a low priority in the human mind in general (relative to other types of information regarding object location and motion).

Author's contributions Dawei Bai: Data analysis, Writing/Editing (lead), Visualization. Brent Strickland: Conceptualization, Methodology, Participant Recruitment, Writing/Editing, Project Supervision.

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Data availability The raw data and the questionnaire used during the experiment are available on Open Science Framework (https://osf.io/3dtmq/).

Code availability The code is not publicly available.

Declarations

Conflicts of interest/Competing interests None of the authors has any conflicts of interest or financial stake in this research.

Consent to participate Participants provided informed consent for their participation. This study was run in 2015. It fell under the framework of noninvasive psychological research and was thus exempted from the need for formal approval from the local (CERES) ethical committee.

Consent for publication Participants provided informed consent for the publication of the data. The individual in Figure 2 has consented for the publication of the image.

The study conformed to the standards required by the Declaration of Helsinki.

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Open practices statement This study was not formally preregistered. The raw data and questionnaire used in the experiment are available on OSF (https://osf.io/3dtmq/).