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Rotating objects cue spatial attention via the perception of frictive surface contact

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ABSTRACT

We report a new attentional cueing effect, which shows how attention models the physical force of friction. Most objects we see are in frictive contact with a 'floor', such that clockwise rotation causes rightward movement and counterclockwise rotation leftward movement. Is this regularity encoded in spatial orienting responses? In Experiment 1, seeing a clockwise-rotating 'wheel' produced faster responses to subsequent targets appearing on the right vs. left (and vice versa for counterclockwise rotation). Thus, when viewing a lone rotating wheel, we orient attention toward where we predict it will move next, assuming frictive floor contact. But what happens if the rotating wheel is seen touching another visible surface? In Experiment 2, rotational cueing was stronger for wheels touching a visible floor, was abolished for wheels near but not touching another surface, and reversed for wheels touching a ceiling. We conclude that the visual system makes an assumption of frictive floor contact, and rapidly analyzes visual cues to frictive contact with other surfaces, in order to orient attention toward where objects are likely to move next.

1. Introduction

One of the most important functions of visual processing is to predict how objects will move, in order to orient attention to where they will be next. For example, if we see a car begin to spin its wheels in the mud, we ought to form a prediction about its future direction of movement, and attend there. Here we report a new attentional cueing effect, which shows how attention models the physical force of friction. When a rotating wheel is seen alone in a display, this orients attention in the direction that the wheel would move if making frictive contact with a 'floor', with clockwise rotation orienting attention rightward, and counterclockwise rotation orienting attention leftward. Interestingly, seeing the rotating wheel touching vs. not touching another surface can modulate and even reverse its cueing effect — indicating rapid analysis of visual cues to frictive contact between objects and surfaces.

1.1. *Seeing forces*

When reasoning about what will happen next in a hypothetical physical situation, people are generally accurate, but sometimes make surprising errors. For example, many participants guess incorrectly that an object dropped from a flying plane will fall straight downward (McCloskey, Washburn, & Felch, 1983), and that a ball passing through a curved tube will follow a curved trajectory upon exiting (McCloskey, Caramazza, & Green, 1980). Such errors suggest that people reason about physical events by using simple heuristic principles (e.g. a belief that objects usually fall straight downward; Caramazza, McCloskey, & Green, 1981). Under normal circumstances these heuristics lead to accurate predictions, but in novel situations, they produce errors (for further discussion of the role of heuristics in physical reasoning, see Gilden & Proffitt, 1989; Gilden & Proffitt, 1994; Kozhevnikov & Hegarty, 2001; Hubbard, 2022; McCloskey et al., 1983; Proffitt, Kaiser, & Whelan, 1990; Proffitt & Gilden, 1989).

Much work in intuitive physics has focused on people's use of heuristics when *explicitly reasoning* about physical situations. However, we also make assumptions about physical regularities much more implicitly, as revealed through biases in how we perceive and remember visual information. Measures of visual performance (e.g. accuracy in reaching out to intercept a falling object), suggest a variety of ways in which predicting and remembering objects' movements reflect physical regularities — including gravity (e.g. McIntyre, Zago, Berthoz, & Lacquaniti, 2001; Nguyen & van Buren, 2023a), momentum (e.g. Freyd & Finke, 1984; Hubbard, 1998), and even internal propulsive forces (e.g. Pratt, Radulescu, Guo, & Abrams, 2010). Much like our perception of other

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visual properties, such as color and shape, impressions about the visual forces acting on objects arise quickly and automatically, and evince close psychophysical relationships with subtle features of the input stimulus (Scholl & Gao, 2013; see also Hafri & Firestone, 2021; Parovel, 2023). Thus, in addition to overt reasoning about physical forces — which tends to be relatively slow, voluntary, less closely tethered to stimulus input, and more influenced by participants' understanding about the demands of the experimental situation — assumptions about physical regularities are also integrated into visual processing itself.[1]

1.2. The current study: friction in attention

The perception of physical forces has long captured the interest of vision scientists (e.g. Bozzi, 1959; Runeson & Frykholm, 1983), but past investigations have only occasionally considered the critical importance of quickly modeling the force of friction. However, visual processing must anticipate the effects of objects' frictive interaction with other surfaces, both in order to predict when they will slow down (Amorim, Siegler, Baurès, & Oliveira, 2015; Hubbard, 1998), and also to predict the onset and direction of *new* movement. Again, imagine a stationary car starting to spin its wheels in the mud — here it is necessary to use information about the wheels' frictive interaction with the ground in order to predict where the car will move next.

Here we tested whether information about friction is integrated into visual predictions about objects' movements, as evidenced by patterns of attentional orienting. In Experiment 1, we found that an isolated rotating object produces a powerful spatial orienting effect toward where the object would move given frictive contact with a 'floor' surface beneath it. In Experiment 2, we asked whether this assumption of frictive floor contact can be overridden by showing the rotating object touching a 'ceiling' above it — and found that this added visual cue to frictive interaction with another surface causes the attentional orienting effect to *reverse*. These results show how an implicit model of the force of friction — based on both prior assumptions and visible cues to surface contact — helps to orient attention toward where an object is likely to move next. Dynamic animations of the displays used in these experiments can be viewed online at https://www.nssrperception.com/project-friction-attention.html.

2. Experiment 1: rotating objects cue spatial attention

When we see an object, it is usually sitting on a surface beneath it, and it is usually in frictive contact with that surface. If these physical regularities are integrated into the operation of visual attention, then viewing an isolated rotating object might automatically orient spatial attention in the direction the object would move if in frictive contact with a 'floor'. If so, in a speeded letter identification task, viewing a clockwise-rotating object might produce faster responses to targets appearing on the right (vs. left), and viewing a counterclockwise-rotating object might produce faster responses to targets appearing on the left (vs. right). See Fig. 1 for a depiction of the stimulus and task used in Experiment 1.

2.1. Method

2.1.1. Participants

150 observers (70 female, 80 male; average age = 25.42 years, *SD* = 3.48) with normal or corrected-to-normal acuity participated. Participants were recruited through the online labor market Prolific (https://prolific.co/), which is often used for studies of this sort. For a discussion of this participant pool's reliability, see Palan and Schitter (2018). Each observer participated in a 15 min online session on the experiment hosting site Pavlovia (https://pavlovia.org/), in return for a small monetary payment. During data collection, 5 participants were excluded and replaced (three who failed to provide complete data, two who at the end of the study rated their attention as less than 70 on a scale from 0 to 100).

The sample size was determined as follows: In a pilot experiment, a within-subjects *t*-test revealed faster responses to letters when their location was congruent with terrestrial rolling vs. incongruent, with an effect size of $d_z = 0.60$. A power analysis conducted using R's pwr library (Champely, 2020) indicated that we would need at least 137 participants to detect this effect with 80% power at an α level of 0.05. We rounded up to the nearest 50, and preregistered a sample size of 150.

2.1.2. Stimuli

Stimuli were created using custom software written using the PsychoPy libraries (Peirce, 2007). On each trial, participants saw a light gray [#C0C0C0] display, which featured a centered 40px-radius 'wheel', divided evenly into 12 alternating middle gray [#666666] and dark gray [#252524] wedges.[2]

2.1.3. Procedure

Each trial was preceded by a 600 ms ITI. At the start of the trial, the wheel appeared and rotated either clockwise or counterclockwise at 240°/s until the end of the trial. At 200 ms, a 30-pix high letter ('H' or 'N', counterbalanced) appeared on the wheel's left or right, and participants identified the letter by pressing the corresponding key as quickly as possible (see Fig. 1). If the participant failed to respond within 2 s of the letter's appearance, the trial ended, and the participant was shown a 500 ms timeout screen with a message reminding them to respond as quickly as possible. In these cases, the trial was recycled to the end of the trial list.[3] The experiment had a 2 (Rotation Direction: Clockwise vs. Counterclockwise) x 2 (Letter Location: Left vs. Right) within-subjects design. Participants completed 8 practice trials, the results of which were not recorded. They then completed 128 trials in a randomized order. Halfway through, they saw a screen with a written message prompting them to take a short break. Preregistrations of the design, analysis procedures and data files can be found at https://osf.io/4qv6h/ (Nguyen & van Buren, 2023b).

2.2. Results

We excluded trials in which the participant reported the letter inaccurately (on average 4.45% of trials), and trials in which the participant's reaction time was >2SDs above their own mean reaction time (on average 1.14% of trials). Reaction times for the remaining trials are depicted in Fig. 2a. A two-way repeated measures Analysis of Variance on response times revealed a main effect of Rotation Direction, $F(1,149) = 14.03$, $p < .001$, $\eta_p^2 = 0.09$, a main effect of Letter Location, $F(1,149) = 6.57$, $p = .011$, $\eta_p^2 = 0.04$, and the hypothesized interaction between Rotation Direction and Letter Location, $F(1,149) = 44.24$, $p < .001$, $\eta_p^2 = 0.23$.

Specifically, participants responded faster on trials in which the wheel rotated Clockwise ($M = 538$ ms) vs. Counterclockwise ($M = 556$ ms), $t(149) = 3.75$, $p < .001$, $d_z = 0.31$, and faster on trials in which the

[1] Analogously, while most people have explicit knowledge that light usually comes from above, many vision scientists speak of a distinct 'light-from-above prior' in the perception of depth from shading cues (e.g. Hershberger, 1970). These theorists are referring to a distinct kind of knowledge, which is implicit, and specifically *visual* — i.e. embedded in the operation of a domain-specific mechanism, which infers from retinal luminance to distal spatial layout.

[2] Because this was an online study, display size and viewing distance were not controlled, and the exact stimulus dimensions (in degrees of visual angle) could thus vary across participants. However, our Prolific settings prohibited participants from accepting the task on a phone, and the experiment required participants to keep their web browser in full screen mode.

[3] In practice, an average of 7.5% of trials were recycled due to timeouts.

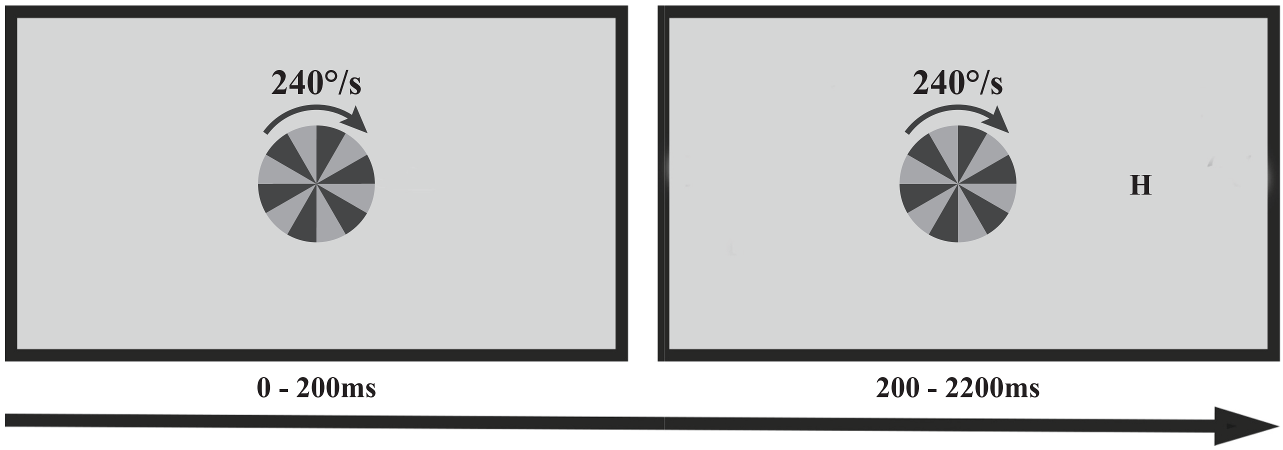

Fig. 1. Cartoon depiction of a trial in Experiment 1. The wheel appeared and began rotating either clockwise or counterclockwise. At 200 ms, a letter ('H' or 'N') appeared, and participants identified the letter by pressing the corresponding key as quickly as possible.

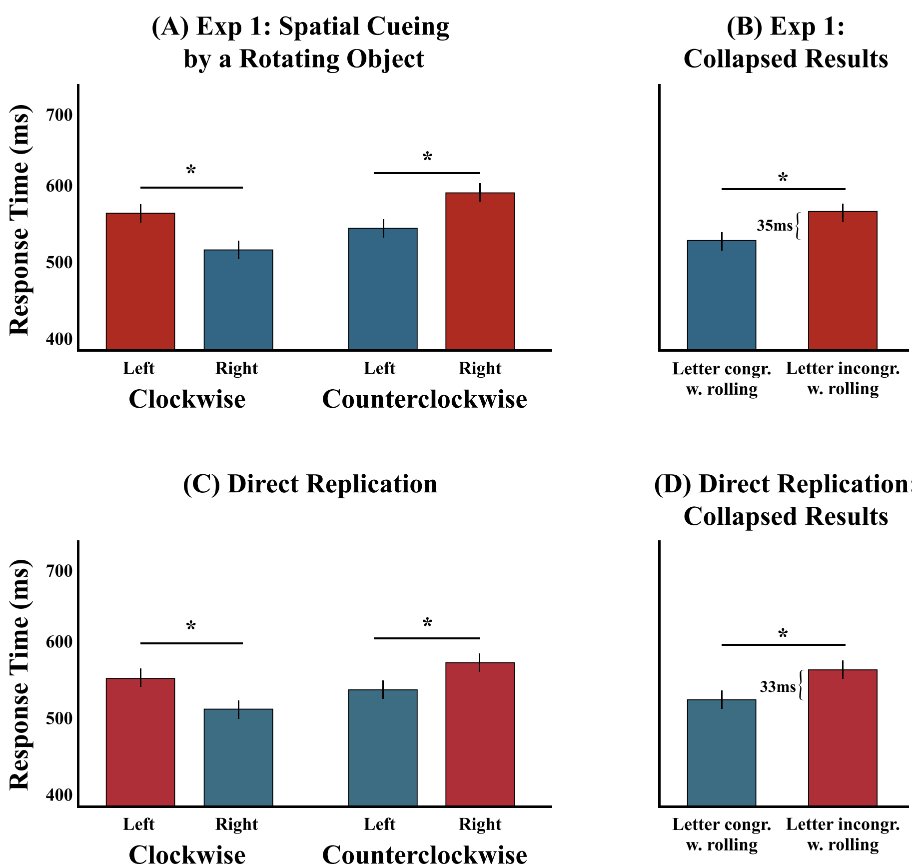

Fig. 2. (a) Results of Experiment 1. The graph depicts average response times in the Clockwise rotation and Counterclockwise rotation conditions, to letters appearing on the wheel's left and right sides. (b) These same results, collapsing the Clockwise-right and Counterclockwise-left conditions in the "Letter congruent with rolling" bar, and the Clockwise-left and Counterclockwise-right conditions in the "Letter incongruent with rolling" bar. (c) Results of Experiment 1's direct replication. (d) A collapsed depiction of these same results. Error bars depict 95% confidence intervals, subtracting out the shared variance.

letter appeared on the Right (M = 542 ms) vs. Left (M = 553 ms), $t(149) = 2.56$, $p = .011$, $d_z = 0.21$. Critically, our hypothesis was supported: Clockwise rotation produced faster response times to letters appearing on the Right (M = 515 ms) vs. Left (M = 561 ms), $t(149) = 6.64$, $p < .001$, $d_z = 0.54$, and Counterclockwise rotation produced faster response times to letters appearing on the Left (M = 544 ms) vs. Right (M = 568 ms), $t(149) = 3.49$, $p < .001$, $d_z = 0.29$. Fig. 2b collapses these results, and shows that participants responded faster to letters appearing in locations congruent with the direction of terrestrial rolling (M = 530 ms) vs. incongruent with terrestrial rolling (M = 564 ms), $t(149) = 6.65$, $p < .001$, $d_z = 0.54$.

2.3. Direct replication

Since this was a new effect, we next directly replicated the experiment on a new sample of 150 participants (92 female, 58 male; average age = 26.8 years, SD = 3.92). During data collection, 6 participants were excluded and replaced (three who failed to provide complete data and three who at the end of the study rated their attention as less than 70 on a scale from 0 to 100).

We excluded trials in which the participant reported the letter inaccurately (on average 2.62% of trials) and trials in which the participant's reaction time was >2SDs above their own mean (on average 1.47% of trials). Reaction times for the remaining trials are depicted in Fig. 2c. A two-way repeated measures Analysis of Variance on response times revealed a main effect of Rotation Direction, $F(1,149) = 18.45$, $p < .001$, $\eta_p^2 = 0.11$, a main effect of Letter Location, $F(1,149) = 4.47$, $p = .036$, $\eta_p^2 = 0.03$, and the hypothesized interaction between Rotation Direction and Letter Location, $F(1,149) = 52.14$, $p < .001$, $\eta_p^2 = 0.26$.

Specifically, participants responded faster on trials in which the wheel rotated Clockwise (M = 529 ms) vs. Counterclockwise ($M = 547$ ms), $t(149) = 4.29$, $p < .001$, $d_z = 0.35$, and faster on trials in which the letter appeared on the Right ($M = 534$ ms) vs. Left ($M = 543$ ms), $t(149) = 2.11$, $p = .036$, $d_z = 0.17$. We again observed the hypothesized effect: Clockwise rotation produced faster responses to letters appearing on the Right ($M = 508$ ms) vs. Left ($M = 551$ ms), $t(149) = 6.51$, $p < .001$, $d_z = 0.53$, and Counterclockwise rotation produced faster responses to letters appearing on the Left ($M = 535$ ms) vs. Right ($M = 559$ ms), $t(149) = 3.66$, $p < .001$, $d_z = 0.30$. Fig. 2d collapses these results. Inspection of this panel reveals that participants responded faster to letters appearing in locations congruent with the direction of terrestrial rolling ($M = 522$ ms) vs. incongruent with terrestrial rolling ($M = 555$ ms), $t(149) = 7.22$, $p < .001$, $d_z = 0.59$.

2.4. Discussion

When a rotating object is presented alone, it orients spatial attention in a way which matches how the object would normally move, assuming contact with a frictive 'floor'. A likely explanation of this result is that, due to the physical regularities of gravity, friction, and momentum, clockwise (counterclockwise) rotation is strongly associated with rightward (leftward) translation, resulting in a learned attentional cueing effect which reflects these physical regularities.

We also observed two main effects which we did not hypothesize, but which suggest straightforward, post-hoc explanations. First, participants were generally faster to respond to letters on the right versus left. Although we did not record information about handedness, the majority of people are right-handed, and this result may reflect faster motor execution with the right hand. Another possible explanation of this result is that all of our participants were literate in the English language, which reads from left to right. As a result of this, following initial capture of attention by the rotating wheel, they may have been faster at deploying attention rightward. Second, on trials with a clockwise rotating wheel (vs. a counterclockwise rotating wheel), participants were in general slightly faster to respond to the target letter, collapsing across letter location. One possible explanation is that clockwise rotation is more familiar than counterclockwise rotation (e.g. from reading clocks), and that this greater familiarity made disengaging attention from the central stimulus more efficient (for a previous observation that disengaging attention is easier for familiar and expected stimuli, see Brockmole & Boot, 2009).

We think that the physical regularity of frictive floor contact results in a correlation between clockwise rotation and rightward movement, and counterclockwise rotation and leftward movement, and that this regularity is embedded in visual processing as an attentional cueing effect. However, an alternative explanation of our results is that participants simply attended more to the top of the wheel, and that this caused an orienting effect in the direction of the motion signals at the top of the wheel. How plausible is this explanation? On one hand, there is some evidence that observers attend more to objects' tops in different contexts, when judging shape similarity (Chambers, McBeath, Schiano, & Metz, 1999). On the other hand, more closely related work on motion processing suggests the opposite — that motion processing is more efficient *lower* in a display (e.g. Zito, Cazzoli, Müri, Mosimann, & Nef, 2016). To foreshadow, the results of Experiment 2 indicate that a bias toward processing motion signals at the top of the wheel is not the explanation of the present results.

3. Experiment 2: reversal of the cueing effect by contact with a 'ceiling'

In Experiment 1, the rotating wheel was always presented alone, without any other surfaces visible. It nevertheless produced a strong spatial orienting effect in the direction the wheel would move if in frictive contact with a floor beneath it. One possibility is that rotating objects always orient spatial attention in a way which assumes frictive contact with a floor. (After all, this assumption is consistent with the vast majority of objects that we see.) But another possibility is that, when a rotating object is seen touching another kind of surface, visible cues to frictive contact are rapidly analyzed, in a way which modulates how the rotating object orients attention. In Experiment 2, we ran another cueing experiment, in order to assess the speed and flexibility with which spatial orienting models the force of friction. Here we tested (1) whether the spatial orienting effect depends on whether the object is shown touching vs. not touching another visible surface, and (2) whether the effect even *reverses* for rotating objects seen in contact with a 'ceiling' (imagine painting your ceiling with a paint roller; here, clockwise rotation of the roller is associated with *leftward* movement).[4]

3.1. Method

Experiment 2 was identical to Experiment 1, except as noted here. 150 new observers (60 female, 90 male; average age = 24.35 years, *SD* = 3.45) with normal or corrected-to-normal acuity each participated in a 30 min online session. On each trial, the wheel was presented centrally, along with a 20px thick gray [#696969] horizontal line, which extended across the full width of the screen. The line was drawn either above or below the wheel, either touching it, or separated by a 50px gap. Thus the experiment had a 2 (Surface Type: Ceiling vs. Floor) x 2 (Surface Contact: Touching vs. Not Touching) x 2 (Rotation Direction: Clockwise vs. Counterclockwise) x 2 (Letter Location: Left vs. Right) within-subjects design. Participants completed 256 trials in a randomized order. Preregistrations of the design, analysis procedures and data files can be found at https://osf.io/4qv6h/ (Nguyen & van Buren, 2023a).

3.2. Results

We excluded trials in which the participant reported the letter inaccurately (on average 1.32% of trials) and trials in which the participant's reaction time was >2SDs above their own mean (on average 3.67% of trials). Fig. 3a depicts the magnitude of the 'terrestrial cueing effect' (i.e. the effect which we hypothesized and observed in Experiment 1) for each of the four conditions, computed as (RT for letters on the side of the wheel incongruent with terrestrial-rolling) − (RT for letters on the side of the wheel congruent with terrestrial-rolling). As can be seen in the figure, in the Floor Touching condition, there was again a strong cueing effect consistent with that observed in Experiment 1. In the Floor Not Touching condition, this effect was greatly reduced. Strikingly, in the Ceiling Touching condition, the cueing effect reversed, and in the Ceiling Not Touching condition, the reversed cueing effect was greatly reduced.

These observations were confirmed with the following statistical tests: a 2 (Surface Type: Ceiling vs. Floor) x 2 (Surface Contact: Touching vs. Not Touching) x 2 (Rotation Direction: Clockwise vs. Counterclockwise) x 2 (Letter Location: Left vs. Right) repeated measures ANOVA on

[4] For a previous experiment in which the perception of friction was manipulated by varying whether an object was seen to be touching vs. not touching another surface, see Hubbard (1995).

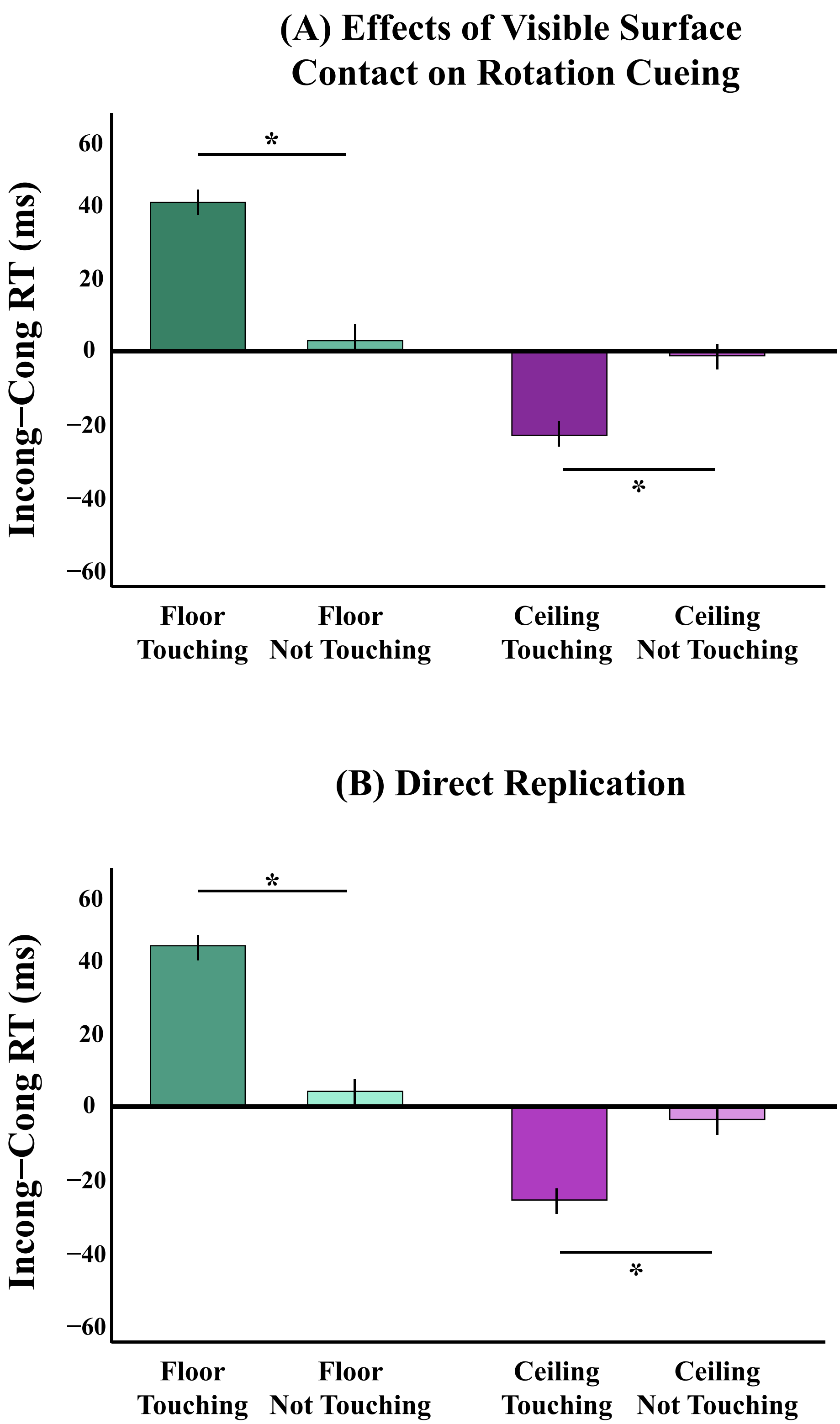

Fig. 3. (a) Results of Experiment 2. For the Floor Touching, Floor Not Touching, Ceiling Touching, and Ceiling Not Touching conditions, the graph depicts the magnitude of the previously observed 'terrestrial cueing effect', computed as (RT for letters on the side of the wheel incongruent with terrestrial-rolling) − (RT for letters on the side of the wheel congruent with terrestrial-rolling). (b) Results of Experiment 2's direct replication. Error bars depict 95% confidence intervals, subtracting out the shared variance.

RTs revealed the hypothesized four-way interaction, $F(1,149) = 136.51$, $p < .001$, $\eta_p^2 = 0.48$.[5] In the Floor Touching condition, participants responded faster to letters located congruently with the direction the wheel would move if in frictive contact with a floor ($M = 523$ ms) vs. located incongruently ($M = 563$ ms), $t(149) = 12.86, p < .001, d_z = 1.05$. In contrast, in the Floor Not Touching condition, the cueing effect was abolished, with no significant difference in RTs for letters located

[5] See supplemental analyses for Experiment 2's complete ANOVA results.

congruently with the direction the wheel would move if in frictive contact with a floor ($M = 544$ ms) vs. located incongruently ($M = 546$ ms), $t(149) = 0.97$, $p = .332$, $d_z = 0.08$. The incongruent − congruent cueing effect was significantly greater in the Floor Touching condition ($M = 40$ ms) than in the Floor Not Touching condition ($M = 2$ ms), $t(149) = 11.52$, $p < .001$, $d_z = 0.94$.

On Ceiling Touching trials, the cueing pattern reversed: now participants responded faster to targets that were *in*congruent with terrestrial rolling ($M = 518$ ms) vs. congruent ($M = 542$ ms), $t(149) = 7.75$, $p < .001$, $d_z = 0.63$. On Ceiling Not Touching trials, there was no reliable cueing effect (incongruent $M = 544$ ms, congruent $M = 545$ ms), $t(149) = 0.24$, $p = .814$, $d_z = 0.14$. The incongruent − congruent cueing effect had a significantly greater magnitude in the Ceiling Touching condition ($M = -24$ ms) than in the Ceiling Not Touching condition ($M = -1$ ms), $t(149) = 8.36$, $p < .001$, $d_z = 0.68$. Thus, rotating objects orient spatial attention differently, depending on how they are touching other visible surfaces.

3.3. Direct replication

Given the importance of direct replications, we next reran the experiment on a new sample of 150 participants (83 female, 67 male; average age = 26.62 years, $SD = 5.26$). We excluded trials in which the participant reported the letter inaccurately (on average 1.35% of trials), and trials in which the participant's reaction time was >2SDs above their own mean (on average 3.39% of trials). Fig. 3b depicts the magnitude of the 'terrestrial cueing effect' for each of the four conditions. As can be seen in the figure, in the Floor Touching condition, there was again a strong cueing effect consistent with that observed in Experiment 1. In the Floor Not Touching condition, this effect was greatly reduced. In the Ceiling Touching condition, the cueing effect reversed, and in the Ceiling Not Touching condition, the reversed cueing effect was greatly reduced.

These observations were confirmed with the following statistical tests: a 2 (Surface Type: Ceiling vs. Floor) x 2 (Surface Contact: Touching vs. Not Touching) x 2 (Rotation Direction: Clockwise vs. Counterclockwise) x 2 (Letter Location: Left vs. Right) repeated measures ANOVA on RTs revealed the hypothesized four-way interaction, $F(1,149) = 129.75$, $p < .001$, $\eta p2 = 0.47$. See supplemental analyses for the full results of this ANOVA. As hypothesized, in the Floor Touching condition, participants responded faster to letters located congruently with the direction the wheel would move if in frictive contact with a floor ($M = 527$ ms) vs. located incongruently ($M = 569$ ms), $t(149) = 13.29$, $p < .001$, $d_z = 1.09$. In contrast, in the Floor Not Touching condition, the cueing effect was abolished, with no significant difference between RTs for letters located congruently with the direction the wheel would move if in frictive contact with a floor ($M = 549$ ms) vs. located incongruently ($M = 553$ ms), $t(149) = 1.54$, $p = .126$, $d_z = 0.13$. The incongruent − congruent cueing effect was significantly greater in the Floor Touching condition ($M = 42$ ms) than in the Floor Not Touching condition ($M = 4$ ms), $t(149) = 11.01$, $p < .001$, $d_z = 0.89$.

On Ceiling Touching trials, the cueing pattern reversed: participants responded faster to targets that were *in*congruent with terrestrial rolling ($M = 525$ ms) vs. congruent ($M = 554$ ms), $t(149) = 5.86$, $p < .001$, $d_z = 0.31$. On Ceiling Not Touching trials, there was no cueing effect (incongruent $M = 547$ ms, congruent $M = 552$ ms), $t(149) = 1.53$, $p = .128$, $d_z = 0.13$. The incongruent − congruent cueing effect had a significantly greater magnitude in the Ceiling Touching condition ($M = -29$ ms) than in the Ceiling Not Touching condition ($M = -5$ ms), $t(149) = 5.95$, $p < .001$, $d_z = 0.49$.

3.4. Discussion

In Experiment 1, a lone rotating wheel oriented spatial attention in a way that was consistent with an assumption of frictive floor contact. In Experiment 2, this cueing effect was present when the rotating wheel was seen touching a surface below it, was abolished when it was near but not touching another surface, and reversed when it was seen touching a 'ceiling'. From these results, we conclude that, when another surface is visible, attentional orienting in response to a rotating object rapidly integrates information about whether the object is in contact with that surface.

The present results suggest that the results of Experiment 1 were not driven by a simple tendency to attend to the top of the wheel and to orient in the direction of motion signals there. If that were the mechanism for rotational cueing of attention, then drawing a salient ceiling above the wheel should shift attention more toward its top, and produce a cueing effect in the same direction as in Experiment 1 (but we observed the reverse cueing effect). In the General Discussion, we return to the question of how these cueing effects may depend on the initial deployment of attention.

One interesting feature of our overall pattern of results is that, in Experiment 1, a lone wheel produced a strong cueing effect — but in Experiment 2, we did not observe reliable cueing effects for a wheel shown hovering near, but not touching, a floor or ceiling. Spatial orienting may assume that objects are near at least one other surface, but that lighting conditions can make this surface difficult to see (e.g. at night, there may be very little luminance contrast between the ground and the sky). Thus, when a rotating object is seen against a uniform background, spatial orienting makes a default assumption that the object is sitting on a floor surface, since this is so common (for a related phenomenon in which the visual system fills-in a physically implied surface, see Little & Firestone, 2021). However, when an object is seen near but not touching a visible surface, this may provide evidence that if the object were touching a floor, that the floor would also be visible, and this strong negative evidence against floor contact may explain the lack of robust cueing in the Not Touching conditions.[6]

4. General discussion

These experiments show that rotating objects cue spatial attention toward where they are likely to move next, in a way which reflects both a default assumption of frictive floor contact, and rapid analysis of visual cues to frictive contact with other surfaces. In Experiment 1, a lone rotating wheel oriented attention in the direction that the wheel would normally move if in frictive contact with a floor. In Experiment 2, rotating wheels oriented attention in a way that integrated visual information about surface contact, with the same rotating wheel cueing attention differently depending on how it was touching vs. not touching another surface. Specifically, when the wheel was shown hovering near but not touching a horizontal surface, cueing was attenuated relative to conditions in which it was shown touching that surface. And when the wheel was shown touching a 'ceiling', it produced a *reversed* cueing effect, matching the direction an object would tend to move if in frictive contact with a ceiling. These results suggest that rotational motion orients spatial attention in a way which reflects (1) past experience seeing objects move in a terrestrial environment, and (2) rapid analysis of visual cues to friction in the current scene.

4.1. Seeing friction as a cause of movement

A rich research tradition holds that we perceive objects not just in terms of their positions and movements, but also in terms of their *causal*

[6] For an airborne object, rotation direction affects the vertical component of the ball's acceleration (through the Magnus effect). Hence, in the Not Touching conditions, we might expect rotation to drive *vertical* cueing effects. Future work should investigate this possibility, though our own efforts to study whether rotating wheels can orient spatial attention upward and downward have uncovered only an overwhelming advantage for targets presented lower in the display.

relationships (for reviews, see Hubbard, 2013a; Hubbard, 2013b; Michotte, 1946/63; Scholl & Tremoulet, 2000). For example, if we see an object move until it is adjacent with another object, at which time the second object moves directly away, the second object's movement will often appear to be caused by the first object (the 'launching effect', Michotte, 1946/63). If the second object then continues to move over a long distance (past the launch's 'radius of action'), the object's movement will appear internally caused (see also Boyle, 1961; De Sá Teixeira, De Oliveira, & Viegas, 2008; Yela, 1954). For an object launched on a high friction surface, there is a smaller 'radius of action', outside of which its continued movement looks self-propelled (Amorim et al., 2015). Thus, impressions of self-propelledness outside the radius of action assume that frictive contact with another surface causes a moving object to slow down.

There is also evidence that we *remember* objects' positions in ways which assume the influence of physical forces, such as momentum, gravity, and friction. For example, when we see a moving object and must report its last-visible position, our memory is displaced in the direction that it was moving, suggesting that we attribute to moving objects the physical property of momentum (e.g. Freyd & Finke, 1984; see Hubbard, 2019 for a review). Interestingly, the amount of forward displacement is reduced if the object is shown moving while touching another surface — demonstrating 'representational friction' (Hubbard, 1995; Hubbard, 1998). As with impressions of self-propelledness outside of the radius of action, the phenomenon of representational friction in memory suggests an implicit visual model of friction as a force that causes objects to slow down.

Our work extends these past results in two ways: First, we show for the first time that implicit knowledge of friction is wired into the operation of *visual attention*. When we view a rotating wheel, this orients attention toward where we predict that it will move next, in a way which assumes frictive contact with a floor, but which can be reversed by visual cues to frictive contact with a ceiling. Second, whereas previous work has focused on how contact with other surfaces slows objects, or prevents their movement, the present experiments demonstrate implicit knowledge that interaction with a surface can help to determine where a stationary rotating object will move next. This suggests that researchers studying observers' explicit phenomenological reports about the perception of forces, causality, and resistance (e.g. Hubbard & Ruppel, 2017; White, 2014) may be able to find cases in which observers report the force of friction, perhaps together with other physical forces, as a cause of objects' movements.

4.2. Physical regularities, statistical learning, and visual attention

In addition to our explicit beliefs about the world, we also hold more implicit visual knowledge, which manifests, for example, in what information we attentionally select for further processing. If attention is an important site for intuitive physical knowledge, then how is this knowledge acquired? The answer is that attention is sensitive to statistical structure (e.g. Chun, 2000; Sisk, Remington, & Jiang, 2019; Zhao, Al-Aidroos, & Turk-Browne, 2013). We hypothesize that the cueing effects that we have reported here reflect statistical learning of associations between objects' rotational movements and their subsequent horizontal positions. Statistical learning may also explain a number of phenomena in which physical expectations are integrated into continuous tracking of moving objects, such that violations of these expectations result in worse tracking performance (e.g. Lau & Brady, 2020; Scholl & Pylyshyn, 1999).

More specifically, Experiment 1's rotational cueing effect may be learned from visual input statistics early in life, for example through observing the movements of wheeled vehicles, for which clockwise rotation is often coupled with rightward movement, and counterclockwise rotation with leftward movement. Strong associations could be learned despite seeing occasional exceptions — such as rotating objects that remain stationary due to being fixed in place (e.g. windmills), or sitting on low-friction surfaces (e.g. ice). It is also noteworthy that the same association between rotation and translation is visible in walking feet — work on biological motion perception has found that when observers are asked to judge the walking direction of a point light walker, they rely heavily on the motion of the feet (Chang & Troje, 2009; Troje & Westhoff, 2006). The results of Experiment 1 show that these same associations between rotation and translation are not only used to make explicit judgments about which direction things will move, but are also encoded in how a task-irrelevant stimulus orients attention. The results of Experiment 2, in which the cueing effect reversed in the Ceiling Touching condition, suggest that this spatial orienting relies on different associations in different visual contexts, corresponding to different locations of frictive contact with different translatory consequences.

It has been suggested that the perception of forces in visual interactions requires matching visual events to stored representations acquired through past haptic interactions with objects (White, 2009, 2012; Wolff & Shepard, 2013). However, as discussed above, visual statistical learning of the co-occurrence of certain directions of rotation with certain directions of translation seems sufficient to produce the observed attentional cueing effects, which implicitly model how frictive surface contact influences objects' movements. Although it is not necessary to invoke the motor production or haptic perception of forces to explain these results, future work should investigate possible influences of nonvisual sensory modalities on the observed attentional cueing effects, as well as possible influences of top-down knowledge.

At some level of analysis, the observed cueing effects might be explainable in terms of a cognitive process which fits noisy sensory data with a cognitive model which realistically simulates how objects are likely to move under the influence of different physical forces (for reviews, see Kubricht, Holyoak, & Lu, 2017; Ullman, Spelke, Battaglia, & Tenenbaum, 2017). The effects may also reflect the use of 'visual heuristics' which only roughly correlate with how objects move given frictive surface contact, but which may fail to precisely predict objects' movements across all situations (Caramazza et al., 1981; Gilden & Proffitt, 1989; Gilden & Proffitt, 1994; McCloskey et al., 1983; Proffitt et al., 1990; Proffitt & Gilden, 1989).[7] The effects could arise in a visual cognitive architecture that represents physical interactions between objects and surfaces compositionally (Hafri & Firestone, 2021), but they are also consistent with different architectures (e.g. connectionist networks) which have sometimes been interpreted as lacking compositionality (Fodor & Pylyshyn, 1988).

4.3. Do these cueing effects depend on how one first attends to the rotating wheel?

We suspect that an observer must first attend to a rotating object before the object can itself orient spatial attention. Past work has shown that new motion strongly captures attention (Abrams & Christ, 2003; Al-Aidroos, Guo, & Pratt, 2010; Smith & Abrams, 2018). Thus, in both of the experiments reported here, it is likely that the onset of the wheel's motion drew participants' attention to it, and that the wheel subsequently cued attention to the left or right, in a way which reflected regularities in how objects tend to move as a result of frictive interaction with other surfaces.

[7] According to one 'heuristic' based account in intuitive physics, observers efficiently predict the slowing effects of frictive surface contact and air resistance on launched objects not by modeling friction, mass, normal force, etc., per se, but rather by attributing to them the property of 'dissipating impetus' (Hubbard, 2013a; Hubbard, 2022; Kozhevnikov & Hegarty, 2001). While it is unclear how the current attentional cueing effects could be explained by an impetus heuristic, the cueing of attention by rotating objects may still be heuristic in nature (i.e. relying on certain shortcuts or assumptions, rather than on a precise model of how multiple forces come together in order to produce frictive propulsion).

As discussed above, in Experiment 1, it is conceivable that observers attended more to the top of the lone rotating wheel than they did to the bottom. Could greater processing of motion signals at the top of the stimulus have explained the observed cueing pattern? This explanation of the results seems unlikely, for two reasons. First, although there is evidence that observers rely more on the tops of objects when making visual similarity judgments (e.g. Chambers et al., 1999), when it comes to motion processing, they tend, if anything, to be more sensitive to motion signals lower in the visual field (e.g. Zito et al., 2016). Second, there is evidence that, when observers attend to multiple features or objects, attention tends to be concentrated near the centroid (midpoint) of their locations (Meyerhoff, Papenmeier, & Huff, 2017). This suggests that attention near the top of the wheel was most likely in the conditions when a ceiling was drawn at its top — but this was, of course, the condition in which we found a *reversed* cueing effect. For these reasons, we believe that the pattern of results across both experiments cannot be explained by a simple bias to attend to the top of the wheel — whereas they are parsimoniously explained by the theory that rotating objects cue attention toward where they are predicted to move next, given different locations of frictive surface contact.

4.4. Conclusion

Clearly, we are able to reason explicitly about physics when we are called upon to do so (for example, by our physics teacher). However, we also possess *implicit* knowledge of physical forces, which is tacitly embedded in how visual cues drive attention. Thus, while it took Isaac Newton years of thinking to develop the model of mechanics described in the *Philosophiæ Naturalis Principia Mathematica*, the present results suggest that it takes just a couple of hundred milliseconds for the spatial orienting of attention to factor in the propulsive consequences of a rotating object's frictive contact with another surface. Here we have shown that the visual system makes assumptions about frictive surface contact in order to predict objects' future movements, in a way which drives a powerful spatial orienting response. Visual processing by default assumes that objects are in frictive contact with a floor, but also rapidly integrates visual cues to frictive contact with other surfaces, in order to orient attention toward where they will move next.

CRediT authorship contribution statement

Hong B. Nguyen: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Visualization, Writing – original draft. **Benjamin van Buren:** Conceptualization, Methodology, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors have no competing interests to declare.

Data availability

Data can be found at https://osf.io/4qv6h

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2023.105655.

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