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

Running Head: Rotating objects cue spatial attention

Word Count: 2000 (Intro + Discussion), 2068 (Method + Results)

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Abstract (150 words)

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 online observers' 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, orienting responses to lone rotating wheels assume frictive floor contact. What happens if the rotating wheel is touching another visible surface? In Experiment 2, rotational cueing was stronger for wheels touching a floor, and reversed for wheels touching a ceiling. In Experiment 3, rotational cueing peaked earlier at faster rotation speeds. Attention by default assumes frictive floor contact, but also uses visible surface contact to generate a model of frictive forces in the scene.

Statement of Relevance

We see objects not just in terms of intuitively visual features, such as their colors and orientations, but also in terms of less-obviously visible properties, such as their masses, and the forces acting upon them. Here we demonstrate that observers perceive the physical force of friction, and that this helps to drive visual attention. In particular, viewing a lone rotating object causes us to shift spatial attention toward where that object would normally move if in frictive contact with a ‘floor’. Moreover, when the rotating object is shown touching another visible surface, attention orients toward where the object would move if in frictive contact with the surface. We conclude that visual processing implicitly models the physical force of friction, and that this model is built rapidly, in less than 1/10th of a second.

Keywords: Visual attention, Perception of causality, Perception of physics, Perception of friction

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 start to spin its wheels in the mud, we ought to form a prediction about where it will move in the future, in order to attend there — and this may benefit from an implicit model of the physical forces that are at play in the scene. Here we report a new attentional cueing effect, wherein viewing a rotating 'wheel' stimulus orients spatial attention. When the rotating wheel is seen alone in the display, this orients attention in the direction that the wheel would move if making frictive contact with a 'floor' (perhaps because most objects we encounter are seen sitting upon a frictive floor surface). 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.

Seeing forces

When we explicitly reason about what will happen next in a hypothetical physical situation, our predictions are often wrong: for example, participants guess incorrectly that an object dropped from a flying plane will fall straight downward (McCloskey et al., 1983), and that a ball passing through a curved tube will follow a curved trajectory upon exiting (McCloskey et al., 1980). However, whereas explicit physical reasoning can be highly error-prone, online measures of visual performance (e.g. accuracy reaching out to intercept a falling object) suggest a variety of ways in which predicting and remembering objects' movements require modeling physical properties — including gravity (e.g. Nguyen & van Buren, in press; McIntyre et al., 2001), momentum (e.g. Hubbard, 1998; Freyd & Finke, 1984), and even internal propulsive forces (e.g. Pratt et al., 2010). Much like our perception of other visual features, impressions about the visual forces acting on objects arise quickly and automatically, and evince close psychophysical relationships with features of the stimulus (e.g. Scholl & Gao, 2013; Scholl & Tremoulet, 2000; White, 2007). Thus, beyond just reasoning about physical forces, we also perceive the forces acting on objects much more directly.

The current study: Seeing *friction*

The perception of physical forces has long captured the interest of vision scientists (e.g. Bozzi, 1959; Runeson & Frykholm, 1983), but so far, there has been little work investigating the perception of friction. However, it is important to perceive how the force of friction acts upon objects, both to predict when they will slow down (Amorim et al., 2015; Hubbard, 1998), but also to predict the onset of movement. Again, imagine a stationary car spinning its wheels in the mud — here it is critical to form a sensitive model of the wheel's frictive interaction with the ground, in order to predict where the car will move next.

Here, we tested whether an implicit model of friction drives 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 congruent with 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 could 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 caused the attentional orienting effect to reverse. In Experiment 3, we replicated these spatial orienting effects and investigated their time course. These results show how an implicit model of the force of friction — based on both prior assumptions and visual cues to surface contact — orients attention toward where an object is likely to move next. Dynamic animations of the displays used in these experiments can be viewed online at [Redacted for peer review].

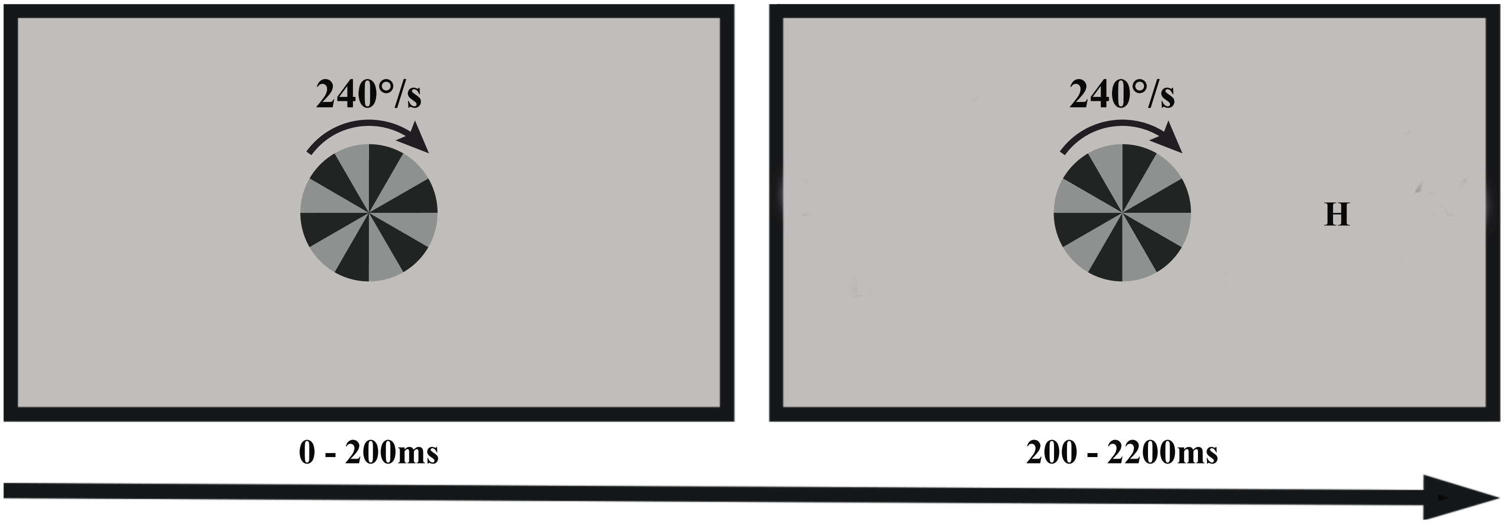


Figure 1: Cartoon depiction of a trial in Experiment 1. The wheel appeared and began rotating either clockwise or counterclockwise. At 200ms, a letter ('H' or 'N') appeared, and subjects identified the letter by pressing the corresponding key as quickly as possible.

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 Figure 1 for a depiction of the stimulus and task used in Experiment 1.

Method

Subjects: 150 subjects (70 female, 80 male; average age=25.42 years, *SD*=3.48) with normal or corrected-to-normal acuity each participated in a 10min online session. 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 subject pool’s reliability, see Palan & Schitter (2018). Each subject 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 and two who at the end of the study rated their attention as less than 70 on a scale from 0-100).

The sample size was determined as follows: In a pilot experiment, a within-subject t-test revealed faster responses to letters when their location was congruent with terrestrial rolling vs. incongruent, with an effect size of d_z=.60. A power analysis conducted using R’s pwr library (Champely, 2020) indicated that we would need at least 137 subjects to detect this effect with 80% power at an α level of .05. We preregistered a sample size of 150 just to be safe.

Stimuli: Stimuli were created using custom software written using the PsychoPy libraries (Peirce, 2007). On each trial, subjects 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.

Procedure: Each trial was preceded by a 600ms 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 200ms, a letter (‘H’ or ‘N’) appeared on the wheel’s left or right, and subjects identified the letter by pressing the corresponding key as quickly as possible (see Figure 1). If the subject failed to respond within 2 seconds of the letter's appearance, the trial ended, and the subject was shown a 500ms 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. The experiment had a 2 (Rotation direction: Clockwise vs. Counterclockwise) x 2 (Letter location: Left vs. Right) within-subject design. Subjects 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. The design and analysis procedures were preregistered at https://osf.io/3c4b7.

Results

We excluded trials in which the subject reported the letter inaccurately (4.45% on average). Reaction times for the remaining trials are depicted in Figure 2a. Clockwise rotation produced faster response times to letters appearing on the right (M=515ms) vs. left (M=561ms), $t(149)=6.64$, $p<.001$, $d_z=0.54$, and Counterclockwise rotation produced faster response times to letters appearing on the left (M=544ms) vs. right (M=568ms), $t(149)=3.49$, $p<.001$, $d_z=0.29$. Figure 2b collapses these results, and shows that subjects responded faster to letters appearing in locations congruent with the direction of terrestrial rolling (M=530ms) vs. incongruent with terrestrial rolling (M=564ms), $t(149)=6.65$, $p<.001$, $d_z=0.54$. Thus, rotation orients spatial attention with a particular regularity: even when viewed in isolation, a rotating object cues attention in the direction that the object would move if in contact with a frictive 'floor'.

Experiment 1b: Direct Replication

Since this was a new effect, we next directly replicated the experiment on a new sample of 150 subjects (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 scal e from 0-100).

We excluded trials in which the subject reported the letter inaccurately (8.77% on average). As depicted in Figure 2c, subjects again responded faster to letters when their location was congruent with the direction that the wheel would roll if making contact with a frictive surface below. Clockwise rotation produced faster responses to letters appearing on the right (M=508ms) vs. left (M=551ms), $t(149)=6.51$, $p<.001$, $d_z=0.53$, and Counterclockwise rotation produced faster responses to letters appearing on the left (M=535ms) vs. right (M=559ms),

$t(149)=3.66$, $p<.001$, $d_z=0.30$. Figure 2d collapses these results. Inspection of this panel reveals that subjects responded faster to letters appearing in locations congruent with the direction of terrestrial rolling (M=522ms) vs. incongruent with terrestrial rolling (M=555ms), $t(149)=7.22$, $p<.001$, $d_z=0.59$.

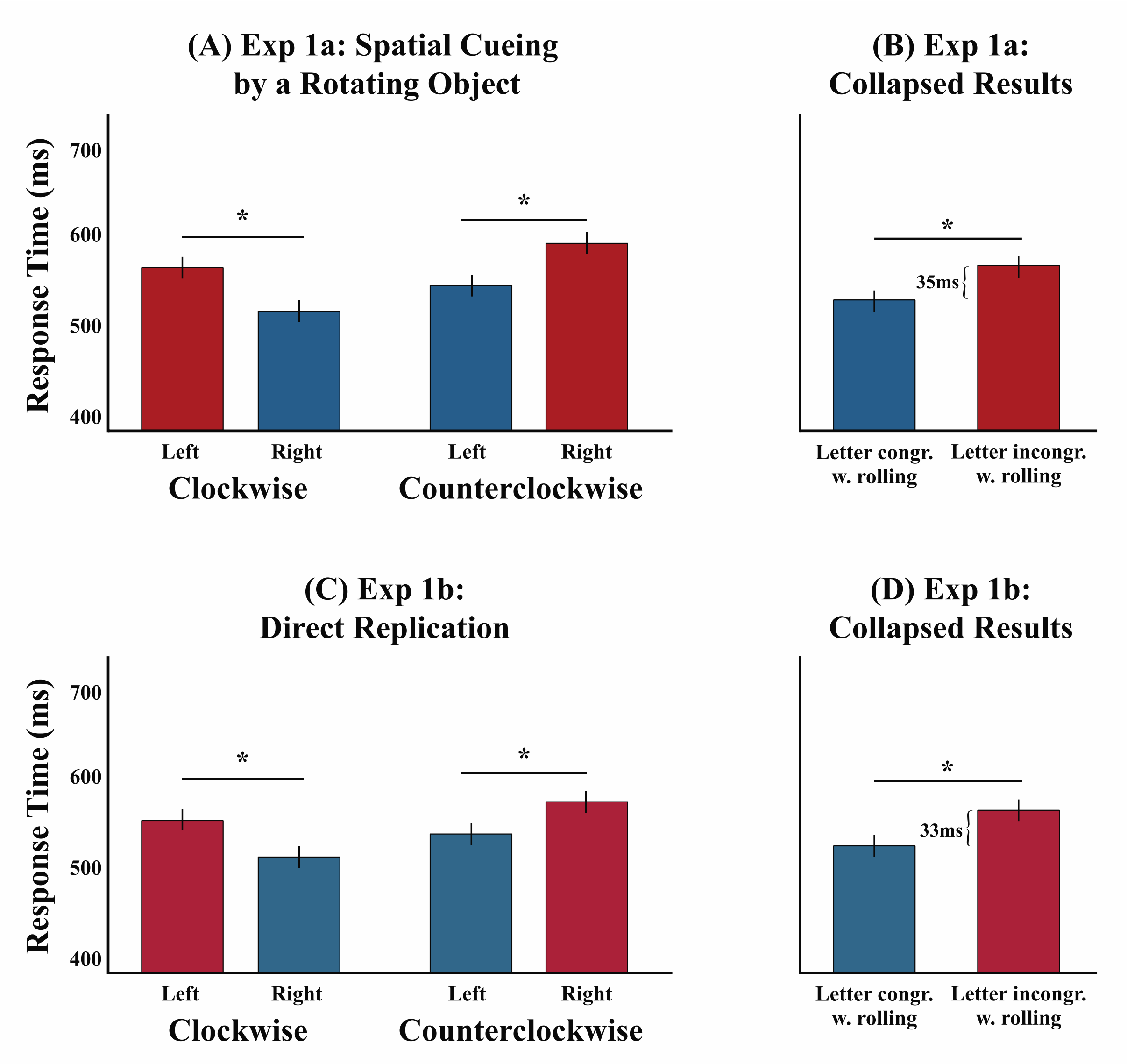


Figure 2: (a) Results of Experiment 1a. The graph depicts average response times in the Clockwise rotation and Counterclockwise rotation conditions, to letters appearing on the wheel's left and right sides. (b) These same results, collapsing the Clockwise-right and Counterclockwise-left conditions in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

Discussion

When a rotating object is presented alone, it orients spatial attention in a way which matches how a rotating object would normally move, assuming contact with a frictive ‘floor’, as is typical for objects in our environment.

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 it were 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, visual cues to surface contact might modulate how the rotating object orients attention. In Experiment 2, we tested whether the spatial orienting effect depends on how the object is touching or not touching another visible surface, and whether the effect 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).

Method

Experiment 2 was identical to Experiment 1, except as noted here. 150 new subjects participated (67 female, 83 male; average age=23.35 years, *SD*=3.45). On each trial, the wheel was presented centrally, along with a 20px stroke horizontal line [#696969], which extended across 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. The design and analyses were preregistered at: https://osf.io/g3s86.

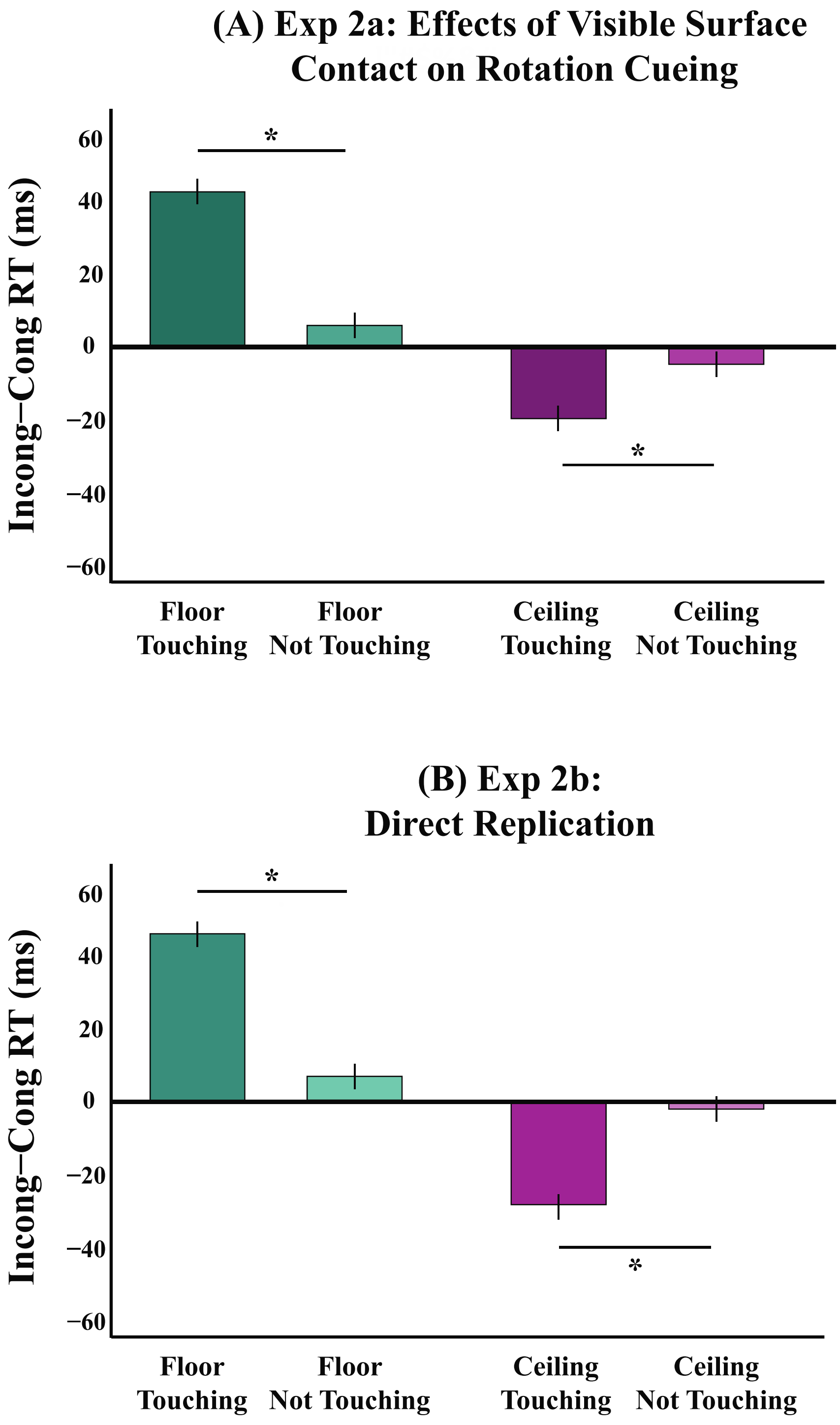


Figure 3: (a) Results of Experiment 2a. For the Floor Touching, Floor Not Touching, Ceiling Touching, and Ceiling Not Touching conditions, the graph depicts the magnitude of the previously observed ‘terrestrial cueing effect’, computed as (RT for letters on the side of the wheel incongruent with terrestrial-rolling) − (RT for letters on the side of the wheel congruent

with terrestrial-rolling). (b) Results of Experiment 2b (a direct replication). Error bars depict 95% confidence intervals, subtracting out the shared variance.

Results

We excluded trials in which the subject reported the letter inaccurately (8.51% on average). Figure 3a depicts the magnitude of the previously observed 'terrestrial cueing effect' 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. Subjects responded faster to letters located congruently with the direction the wheel would move if in frictive contact with a floor (M=540ms) vs. located incongruently (M=584ms), $t(149)=9.38$, $p<.001$, $d_z=0.77$. In contrast, in the Floor Not Touching condition, the cueing effect was abolished, with equally fast RTs for letters located congruently with the direction the wheel would move if in frictive contact with a floor (M=522ms) vs. located incongruently (M=527ms), $t(149)=0.89$, $p=.374$, $d_z=0.07$. The incongruent − congruent cueing effect was significantly greater in the Floor Touching condition (M=43ms) than in the Floor Not Touching condition (M=5ms), $t(149)=5.69$, $p<.001$, $d_z=0.47$.

The results for the Ceiling Touching and Ceiling Not Touching conditions are depicted in Figure 3a's two rightmost columns. Strikingly, on Ceiling Touching trials, the cueing pattern reversed: now subjects responded faster to targets that were *in*congruent with terrestrial rolling (M=548ms) vs. congruent (M=567ms), $t(149)=3.76$, $p<.001$, $d_z=0.31$. On Ceiling Not Touching trials, there was no reliable cueing effect (incongruent M=534ms, congruent M=537ms, $t(149)=0.60$, $p=.556$, $d_z=0.05$). The incongruent − congruent cueing effect had a significantly greater magnitude in the Ceiling Touching condition (M=-19ms) than in the Ceiling Not Touching condition (M=-3ms), $t(149)=2.30$, $p=.023$, $d_z=0.20$. Thus, rotating objects orient spatial attention differently, depending on how they are touching other visible surfaces.

Experiment 2b: Direct Replication

We next reran the experiment on a new sample of 150 subjects (60 female, 90 male; average age=25.62 years, SD=4.26). We excluded trials in which the subject reported the letter inaccurately (7.54% on average). Figure 3b depicts the magnitude of the previously observed '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. Subjects responded faster to letters located congruently with the direction the wheel would move if in frictive contact with a floor (*M*=528ms) vs. located incongruently (*M*=574ms), *t*(149)=9.31, *p*<.001, d_z=0.76. In contrast, in the Floor Not Touching condition, the cueing effect was abolished, with equally fast RTs for letters located congruently with the direction the wheel would move if in frictive contact with a floor (*M*=545ms) vs. located incongruently (*M*=551ms), *t*(149)=1.33, *p*=.186, d_z=0.11. The incongruent − congruent cueing effect was significantly greater in the Floor Touching condition (*M*=46ms) than in the Floor Not Touching condition (*M*=6ms), *t*(149)=5.71, *p* <.001, d_z=0.50.

The results for the Ceiling Touching and Ceiling Not Touching conditions are depicted in Figure 3b's two rightmost columns. Once again, on Ceiling Touching trials, the cueing pattern reversed: subjects responded faster to targets that were *in*congruent with terrestrial rolling (*M*=530ms) vs. congruent (*M*=553ms), *t*(149)=4.67, *p*<.001, d_z=0.38. On Ceiling Not Touching trials, there was no reliable cueing effect (incongruent *M*=541ms, congruent *M*=550ms, *t*(149)=1.73, *p*=.075, d_z=0.15. The incongruent − congruent cueing effect had a significantly greater magnitude in the Ceiling Touching condition (*M*=-23ms) than in the Ceiling Not Touching condition (*M*=-8ms), *t*(149)=2.24, *p*=.026, d_z=0.20.

Discussion

In Experiment 1, a lone rotating wheel oriented spatial attention in a way that assumed frictive floor contact. In Experiment 2, this cueing effect was present when the wheel was shown touching a surface below it, was abolished when it was shown near but not touching another surface, and reversed when the wheel is shown touching a 'ceiling'. From these results, we conclude that, when other surfaces are visible, spatial orienting of attention integrates information about whether objects appear to be in contact with those surfaces.

Experiment 3: Effects of Rotation Speed

How quickly does this analysis occur? The results so far imply that visual information about frictive surface contact is extracted rapidly, such that it is able to influence a speeded letter identification response in under half a second. In our final experiment, to study how this model of friction is constructed over time, we manipulated (1) the speed at which the object rotated, and (2) the duration for which the rotating object was presented prior to the appearance of the letter (the stimulus-onset asynchrony, or SOA). We sought to measure the time course of the cueing and reverse-cueing effects from Experiment 2's Floor Touching and Ceiling Touching conditions. We predicted that wheels rotating at faster speeds might produce cueing effects that appeared and peaked earlier.

Method

Experiment 3 was identical to Experiment 2, except as noted here. All the design and analysis procedures were preregistered at https://osf.io/mb8uy. 900 new subjects (427 female, 473 male; average age=27.32 years, *SD*=4.63) participated. Rotation Speed and SOA were varied between-subjects, and Surface-Type, Rotation Direction and Letter Location were varied within-subjects, in a 3 (Rotation Speed: 120°/sec vs. 240°/sec, vs. 360°/sec) x 3 (SOA: 100ms vs. 200ms vs. 300ms) x 2 (Surface-Type: Ceiling vs. Floor) x 2 (Rotation Direction: Clockwise vs. Counterclockwise) x 2 (Letter Location: Left vs. Right) design.

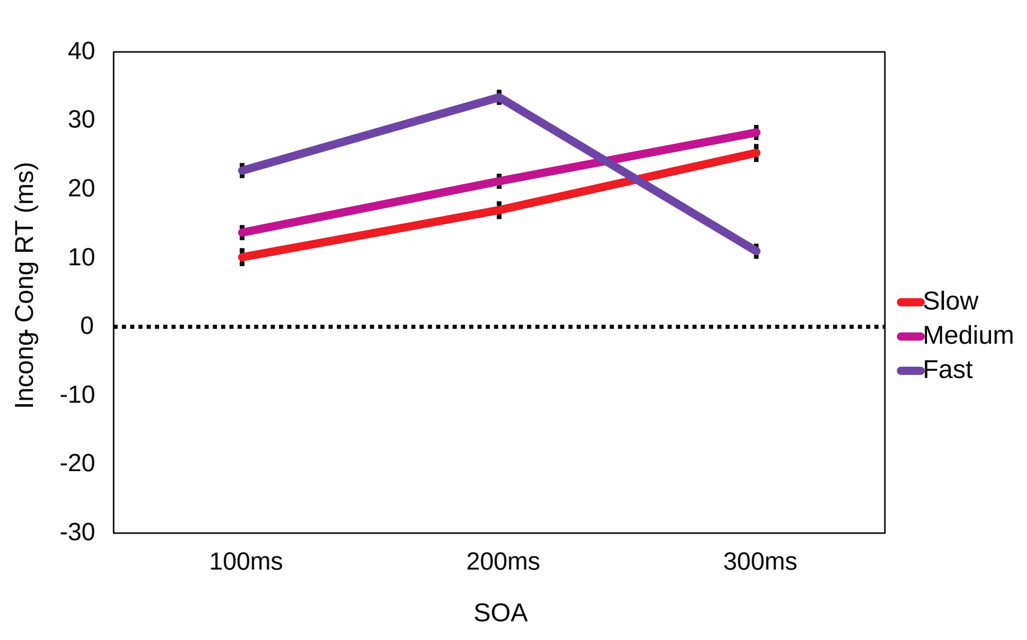
Results

We excluded trials in which the subject reported the letter inaccurately (8.76% on average). Figure 4 depicts the cueing effect shown in the (A) Floor-touching and (B) Ceiling-touching conditions, again 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). Inspection of the figure reveals that, for both Floor-touching and Ceiling-touching displays, subjects who saw faster rotation speeds had cueing effects with earlier time courses. This impression was confirmed with a 2 (Surface-Type: Ceiling vs. Floor) x 3 (Rotation Speed: 120°/sec vs. 240°/sec vs. 360°/sec) x 3 (SOA: 100ms vs. 200ms vs. 300ms) analysis of variance (ANOVA), with the cueing effect as the dependent measure, which revealed a main effect of Surface-Type ($F(1, 1782)=213.08$, $p<.001$, $np^2=0.11$), a 2-way interaction between Surface Type and SOA ($F(2, 1782)=6.88$, $p<.001$, $np^2=0.01$), a 2-way interaction between Rotation Speed and

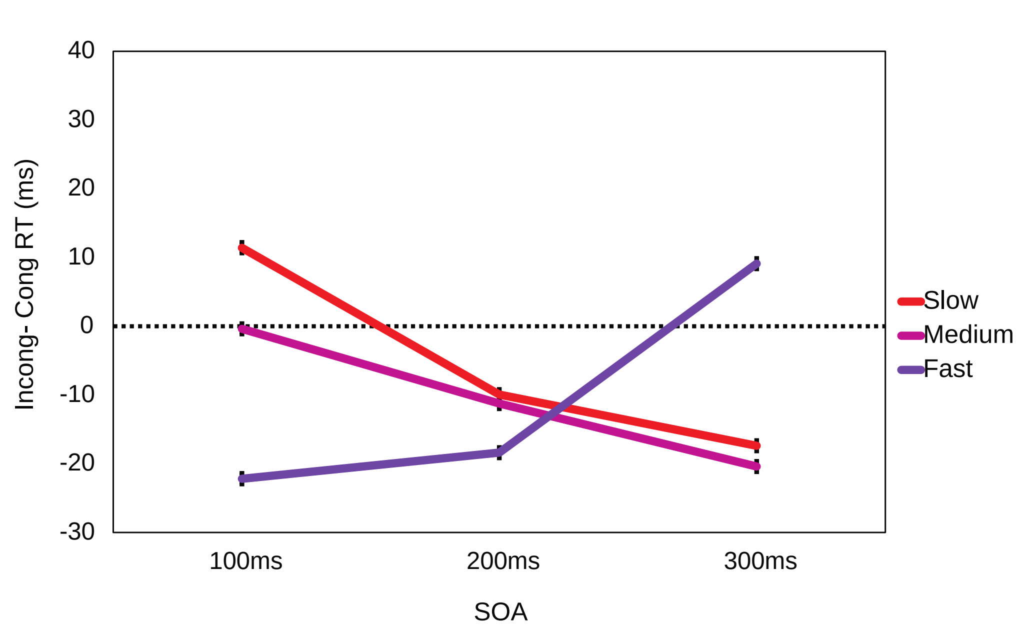
SOA ($F(4, 1782)=2.45$, $p=.040$, $np^2=0.01$), and a 3-way interaction ($F(4, 1782)=17.87$, $p<.001$, $np^2=0.04$).

Figure 4a depicts the cueing effect that subjects showed in the Floor condition, broken down by which Rotation Speed and SOA they saw. For 120°/sec rotation speed subjects, a small cueing effect was already present at 100ms ($M=10$ms), $t(99)=2.40$, $p=.019$, $d_z=0.24$, and became stronger as SOA increased, with a significantly stronger cueing effect at 300ms ($M=25$ms) than at 100ms ($M=10$ms), $t(198)=2.40$, $p=.013$, $d=0.40$. Similarly, for 240°/sec rotation speed subjects, a small cueing effect was already present at 100ms ($M=14$ms), t(99)=2.40, $p=.018$, $d_z=0.24$ and became stronger as SOA increased, with a significantly stronger cueing effect at 300ms ($M=28$ms) than at 100ms ($M=14$ms), $t(198)=2.01$, $p=.040$, $d=0.30$. For 360°/sec rotation speed subjects, the cueing effect was already present at 100ms ($M=23$ms), $t(99)=3.86$, $p<.001$, $d_z=0.40$, peaked at 200ms ($M=33$ms), $t(99)=10.51$, $p<.001$, $d_z=0.86$, and by an SOA of 300ms ($M=11$ms) fell to below the magnitude of the 100ms SOA cueing effect, $t(198)=2.00$, $p=.040$, $d=0.30$.

Figure 4b depicts the cueing effect that subjects showed in the Ceiling condition, broken down by which Rotation Speed and SOA they saw. Inspection of this panel indicates a very different pattern of results: For subjects who saw the wheel rotating at the slowest speed of 120°/sec, at the shortest SOA of 100ms there was a cueing effect in the direction of terrestrial rolling ($M=11$ms), $t(99)=2.27$, $p=.025$, $d_z=0.23$. But, by an SOA of 200ms, the cueing effect flipped to match the reversed cueing pattern previously observed for wheels in contact with a ceiling ($M=-10$ms), $t(99)=2.67$, $p=.009$, $d_z=0.27$. And by an SOA of 300ms, the reversed cueing effect had become stronger ($M=-17$ms), $t(198)=2.00$, $p=.041$, $d=0.30$. For subjects who saw the wheel rotating at the medium speed of 240°/sec, at an SOA of 100ms there was no systematic cueing effect, ($M=-0.36$ms), $t(99)=0.07$, $p=.947$, $d_z=0.01$, but by an SOA of 200ms there was a robust reversed cueing effect ($M=-11$ms), $t(99)=2.73$, $p=.008$, $d_z=0.30$, and by an SOA of 300ms this reversed cueing effect became slightly stronger ($M=-20$ms), $t(198)=2.22$, $p=.027$, $d=0.32$. For subjects who saw the wheel rotating at the fast speed of 360°/sec, at an SOA of 100ms there was already a reversed cueing effect ($M=-22$ms), $t(99)=5.20$, $p<.001$, $d_z=0.52$. At an SOA of 200ms this reversed cueing effect was slightly weaker ($M=-18$ms), $t(198)=0.69$, $p=.494$, $d=0.10$, and by an SOA of 300ms the influence of ceiling contact on spatial orienting expired, such that we observed a regular cueing effect (*M*=9ms), with faster responses to targets in locations congruent with terrestrial rolling, $t(99)=2.57$, $p=.012$, $d_z=0.30$.



(A) Exp 3: Effects of Rotation Speed and SOA on Floor Cueing



(B) Exp 3: Effects of Rotation Speed and SOA on Ceiling Cueing

Figure 4: (a) Results of Experiment 3's Floor Touching condition for each between-subjects rotation speed and SOA condition. The cueing effect is again 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 3's Ceiling Touching condition for each between-subjects rotation speed and SOA condition. Error bars depict 95% confidence intervals.

Discussion

This experiment replicated the cueing and reverse cueing effects observed in the Floor-touching and Ceiling-touching conditions of Experiment 2, and measured how rotation speed influenced the time course of both effects. In general, faster-rotating wheels caused the relevant cueing effect to peak at an earlier SOA. The pattern of results in the ceiling condition suggests that it takes the visual system some time to integrate visual cues to surface contact when predicting objects' future locations. Specifically, when subjects saw an object touching a ceiling, if it rotated slowly, then it initially oriented attention in the direction it would move given contact with a floor, and only later (after 200ms of exposure) did slow rotation orient attention in the direction the object would move given frictive contact with the ceiling. Thus, for slowly-rotating objects, it takes around 200ms to integrate visual cues to contact with a ceiling, in order to produce a reversed cueing effect. In contrast, when the stimulus rotated at the fastest speed, the reversed ceiling cueing effect was already present at the shortest SOA of 100ms, and by 300ms it expired (producing the default floor cueing effect). Overall, these results confirm the rapid speed with which orienting responses to rotating objects integrate visual cues to frictive contact with other surfaces.

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 online analysis of visual cues to frictive contact in the current scene. In Experiment 1, a lone rotating wheel cued 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 frictive 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 line, cueing was attenuated relative to conditions in which it was shown touching a line. 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. Experiment 3 explored the time course over which visual cues to surface contact drive orienting. For quickly rotating objects, we found robustly different cueing effects for the floor touching vs. ceiling touching trials already at 100ms. This indicates a rapid perceptual analysis of visual cues to physical surface contact in the scene (particularly for quickly rotating objects) to orient attention to where an object will move next. In summary, rotational motion cues spatial attention in a way which reflects (1) past experience seeing objects move in a terrestrial environment, and (2) a rapid analysis of visual cues to friction in the current scene.

Seeing friction as a cause of movement

When we see an object move, we also recover rich information about *why* it is moving. For example, if we see one object move until it is adjacent to another object, and the second object begins to move directly away at the moment of contact, then the second object's movement will be seen as caused by the first object (the 'launching effect'; Michotte, 1946/63). However, if the second object continues to move over a great distance (outside the launch's 'radius of action'), then this movement will instead appear driven by an internal force (see also Boyle, 1961; Yela, 1954). For objects seen moving along higher friction surfaces, there is a reduced 'radius of action' beyond which the object begins to look self propelled (Amorim et al., 2015). Thus, visual impressions of self-propelledness outside of the radius of action suggest the implicit logic that, as an object moves, the force of friction tends to cause it to slow down.

There is also evidence that we *remember* objects' positions in ways which assume physical regularities, 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 — an effect which has been called '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. Similarly, memory for objects' positions is sensitive to visual cues to physical support. For example, the remembered position of an isolated object is reliably displaced downward ('representational gravity'; e.g. Hubbard 1990; see Hubbard, 2020 for a review). However, there is no downward displacement in memory for objects shown sitting upon a surface (Bertamini, 1993). These studies have focused on situations in which the visual system predicts that contact with another surface will cause an object to slow down, or prevent it from moving altogether.

Our work extends these past results in two ways: First, we show for the first time that implicit knowledge of friction drives *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 friction often plays a more *positive* role in determining how a rotating object will move next. When predicting where an object will move, the visual system models frictive interaction with another surface not only as a constraint on movement, but also as a cause.

Conclusion

Clearly, we are able to *reason* about physics when we are called upon to do so (for example, by our physics teacher). But in addition to reasoning about forces, we also rapidly *perceive* information about the forces acting on objects. Thus, while it took Isaac Newton years of thinking to develop the model of mechanics described in the *Philosophiæ Naturalis Principia Mathematica*, during online viewing, it takes as little as 100ms 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.

Open Practices Statement

The data for “Rotating objects cue spatial attention via the perception of frictive surface contact” are publicly accessible at OSF https://osf.io/4qv6h/. All experiments were preregistered at OSF https://osf.io/4qv6h/registrations. Demos of all conditions may be viewed at [link redacted for double blind peer review]. Code for the study will be made available upon request.

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