# Contact angle uncertainty influences perceived causality in launching events

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**Abstract**

Humans can perceive causality when viewing collision-like interactions between plain, two-dimensional shapes. To what extent subjective causality reports arise from the physical plausibility of events as predicted by Newtonian physics remains an open question. Here we measured each participant's perceptual judgments about the contact point angle ($\alpha$) and their causality judgments about the target ball's trajectory offset ($\beta$) using Michotte's launching paradigm. Our results showed that subjective causality reports decreased as the target's trajectory deviated further from the physically plausible angle, confirming the important role of physical plausibility in causal perception. Moreover, as uncertainty about $\alpha$ increased, participants were more likely to report events with larger $\beta$ as causal, and their causality reports were more sensitive to changes of $\beta$, consistent with a mental physics model that incorporates $\alpha$. These findings align with predictions of causality perception under a Noisy Newton framework, and provide experimental evidence using individualized uncertainty estimates.

**Keywords:** causality; launching events; psychophysics

## Introduction

Humans are surrounded by a world filled with interacting objects and unfolding events. Inferring the cause and effect relationship between these events can be important for predicting future outcomes, which is essential for survival. Although defining causality philosophically is still challenging (Pearl, 2022), humans generally show a consensus in attributing causes to outcomes. They are not only able to engage in formal reasoning, inferring causality based on structural and probabilistic knowledge of events (Rottman & Hastie, 2014), but also form intuitive causality judgments by simply viewing objects interacting with one another (Gerstenberg, Goodman, Lagnado, & Tenenbaum, 2021; Michotte, 1963).

One of the simplest paradigms that can elicit a sense of causality is the launching paradigm (Michotte, 1963). In Michotte's launching paradigm, participants observe a display where one object (the "launcher") moves toward another initially stationary object (the "target"), where both of the objects are usually simple shapes (e.g. squares or disks). The two objects make contact, and the target starts to move after the collision. Participants are then asked to judge whether and/or to what extent the launcher caused the target's movement. Michotte (1963) conducted experiments with systematic variations in spatial and temporal dynamics, demonstrating that participants reported having perceived causality immediately and robustly in this sequence of events. Since then, important spatial and temporal factors that influence the perception of causality have been widely studied. For example, the perception of causality decreases as the spatial gap between the objects increases (i.e. the objects do not actually touch; Schlottmann, Ray, Mitchell, & Demetriou, 2006), or as the delay between the collision and the second object's movement increases (Shanks, Pearson, & Dickinson, 1989). Causality perception has been found to be influenced by adaptation to the launching stimulus and the objects' perceived surface properties (Arnold, Petrie, Gallagher, & Yarrow, 2015; Kominsky & Scholl, 2020; Rolfs, Dambacher, & Cavanagh, 2013), implying a role of early perceptual processing of the visual properties of the animation in causal impressions. In addition, factors beyond early perceptual processing of the visual scene, especially the realism of the launching display in terms of motion dynamics (e.g. momentum and friction; Meding, Bruijns, Schölkopf, Berens, & Wichmann, 2020), also influence subjective causality reports.

The relationship between the perception of causality and physical realism has been debated since Michotte (1963). Michotte's work (see below) seemed to suggest that humans perceive causality even when events deviate from physical realism. As participants can rapidly learn causal relation from just a single exposure, even highly unrealistic sequences can elicit high causality ratings in typical experiments where participants repeatedly report their causal perceptions (Bechlivanidis, Schlottmann, & Lagnado, 2019). Additionally, postdictive processing has been shown to influence whether observers perceive a causal launching event or a non-causal passing event, indicating that information obtained shortly after the collision also shapes causal perception and that causality is not constructed as a direct and instantaneous representation of reality (Choi & Scholl, 2006; Newman, Choi, Wynn, & Scholl, 2008). On the other hand, previous findings on temporal and spatial factors suggest that causality reports are closely related to the physical plausibility of events, with physically plausible events being more likely to be perceived as causal (White, 2012). The Noisy Newton framework suggests that people have intuitive knowledge about physics, limited by their perceptual uncertainty, and they make predictions accordingly (Kubricht, Holyoak, & Lu, 2017; Gerstenberg et al., 2021). In the context of a launching event involving two objects, the Noisy Newton framework would predict that humans compute the probabil-



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ity of a causal collision given their observations of the two objects: $p(\text{caused by collision}|\text{observations})$. Given an approximate mental model of Newtonian physics, this probability can be inferred from the combination of a prior about the probability of collision, and a likelihood that under the assumption of correct collision physics the perceived pre-collision and during-collision state would yield the perceived post-collision state. Due to the uncertainty of perceptual input, the inferred outcome can vary, and sometimes deviate from exact Newtonian predictions.

Several studies have provided supporting evidence for this framework. Gerstenberg, Goodman, Lagnado, and Tenenbaum (2015) have shown that humans' causal judgments in events of balls colliding are linked to their counterfactual judgments, which can be well-predicted by a Noisy Newton model. This idea was further tested and supported by a computational counterfactual simulation model (Gerstenberg et al., 2021). Sanborn, Mansinghka, and Griffiths (2013) examined mass judgment in launching events, and developed computational models under the Noisy Newton framework for both mass judgments and causality judgments. Their launching display involved two squares colliding on a horizontal plane. Participants were asked to judge which of the two squares was heavier, which was not directly observable from the display but could be inferred from the velocities of the squares before and after collision. The results showed that a Noisy Newton model predicted human mass judgment data better than simple heuristics models, and that its predictions quantitatively aligned well with human causality judgments.

Despite the supporting evidence, the Noisy Newton framework still has open questions. One important factor that has not been addressed within the Noisy Newton framework is the role of individual differences in perceptual uncertainty. While previous studies have typically assumed general (average) uncertainty values, individual uncertainties can vary substantially and may influence people's judgments of causality. Another factor concerns the representativeness and generalizability of the launching displays used in previous studies. One aspect of launching displays that has not yet been considered under the Noisy Newton framework is the interplay between launcher and target direction. Most previous studies have examined collisions in a head-on scenario, with objects placed and moving along one continuous line. However, real-world interactions involve object collisions that are more complex than in the common 1D scenario. For instance, a billiard ball can hit another off-center and cause it to move in a different direction. Nonetheless, we perceive causality in this scenario. Seemingly contrary to this intuition, Michotte (1963) found that observers' causality perception became weaker as the angle between the launcher's pre-collision trajectory and the target's post-collision trajectory increased. Michotte (1963) interpreted this results as reflecting the increased difficulty of integrating the two trajectories as one from the perspective of Gestalt psychology, implying that the two trajectories should have the same direction.

This interpretation is inaccurate from the perspective of physics: in the collision of two balls, a head-on collision ensures that the target would move in the same direction as the launcher, but a non-head-on collision (e.g. a glancing collision) allows the target ball to move to a different direction. In Michotte (1963) and following studies, the launcher always moves directly towards the target, causes a head-on collision, and stops right after the collision. The target moves at a direction with an angle offset from *the launcher's direction*. This setup conflates two angles: (1) the angle of the contact point $\alpha$, defined as the angle from the contact point to the cardinal direction, which determines the direction of the target ball after collision (see the next section and Figure1), and (2) the offset angle $\beta$, defined as the angle between the actual direction of the target ball and its physically plausible direction. In most previous studies, the launcher always moves directly towards the target, causing a head-on collision (i.e. $\alpha = 0$), while the angle offset $\beta$ is manipulated by researchers. As this angle offset increases, causality reports decrease (Badler, Lefèvre, & Missal, 2012; Straube & Chatterjee, 2010). Therefore, measuring how $\alpha$ and $\beta$ influence reported causality allows us to assess to what extent a Noisy Newton model predicts the perception of causality in a more general collision.

In this study, we use Michotte's launching paradigm in a 2D display and focus on how causality judgments are influenced by factors that affect the target ball's trajectory. In the first experiment, we measure participants' perceptual uncertainty regarding the contact point angle $\alpha$. In the second experiment, we measure how the same participants' subjective causality reports change as a function of the angle offset between the target ball's trajectory and its expected direction $\beta$. The target ball's trajectory is physically plausible besides the manipulation of angles: the two balls make contact, the target ball starts moving immediately after the collision, and the magnitude of its velocity is as predicted by Newtonian physics of two balls of the same mass in an elastic collision. As confirmed by previous research that causality is positively associated with physical plausibility (White, 2012), we expect that causality reports would decrease as $\beta$ increases. Moreover, we examine the following predictions from a Noisy Newton model: if an approximate mental model of physics is used to predict the trajectory of the target, then $\alpha$ should be included in this model. Therefore, uncertainty of $\alpha$ should influence participants' threshold of accepted $\beta$: when uncertainty of $\alpha$ is high, the posterior inference of causality based on the target's trajectory would be biased by the prior and other sources of information in the observed event. Given that most spatial and temporal cues in our setting (except for $\beta$) are consistent with a physically plausible collision, higher threshold of $\beta$ should be observed for greater uncertainty about $\alpha$. We also expect the uncertainties of $\alpha$ and $\beta$ to be correlated, as these angles should be the only two factors that determine the direction of the target's observed trajectory under the Newtonian physics model. While the direction of this correlation is difficult to predict due to the complex nature of the model and the information involved, we still expect a correlation.

To test these hypotheses within an individual participant, we manipulate the orientation and the speed of the display. We expect that angle uncertainties for the moving disks are influenced by the well-known oblique effect (Gros, Blake, & Hiris, 1998) and also by display speed, allowing us to vary perceptual uncertainty within an individual. To the extent that these hypotheses are general and that participants do not use diverse strategies for reporting causality, we also expect these predictions to hold between individuals.

# Methods

## The physics of general elastic collision

In this study, we extend the traditional head-on collision scenario to general elastic collision of two balls. First, we describe the physics of elastic collision, and prove that the target ball could move in a direction different from the launcher's direction, and that this direction is determined by the angle of the contact point.

A launching event involves two balls, where ball $b$ initially stays stationary and ball $a$ moves with velocity $\vec{u}_a$ towards ball $b$. For simplicity, initially the two balls are positioned horizontally along the cardinal direction. According to Newton's law I, assuming no friction or external forces, ball $a$ maintains its constant velocity. Ball $a$ will collide into ball $b$ as long as the direction of its speed $\theta_{\vec{u}_a}$ is no larger than $\sin^{-1}((R_a+R_b)/d)$, where $d$ denotes the initial distance between the balls, $R_a$ and $R_b$ denote the radii of the balls, respectively. The largest possible contact point angle $\alpha$ (explained below) is therefore $\cos^{-1}((R_a+R_b)/d)$.

During collision, the force between the balls causes ball $b$ to move from its stationary state. In an elastic collision, velocities of both balls before and after collision adhere to the conservation of momentum (Eq. 1) and the conservation of kinetic energy (Eq. 2):

$$m_a\vec{u}_a + m_b\vec{u}_b = m_a\vec{v}_a + m_b\vec{v}_b \quad (1)$$

$$\frac{1}{2}m_a u_a^2 + \frac{1}{2}m_b u_b^2 = \frac{1}{2}m_a v_a^2 + \frac{1}{2}m_b v_b^2 \quad (2)$$

In a head-on collision (Figure 1, left panel), the direction of $\vec{u}_a$, the centers of the balls, and the contact point, always remain on the same line. The line connecting the contact point and the center of ball $b$ form an angle $\alpha$ of $0°$ with the cardinal direction (i.e. the initial line of centers). After collision, the target ball moves at velocity $\vec{v}_b$, and its direction $\theta_{\vec{v}_b}$ must be the same as the direction of the launcher's initial velocity $\theta_{\vec{u}_a}$. Depending on the relative mass of the two balls, the launcher could completely stop (if $m_a = m_b$), keep moving forward (if $m_a > m_b$), or bounce backward (if $m_a < m_b$).

In general collisions (Landau & Lifshitz, 2013, pp. 44–47), ball $b$ is not necessarily placed on the line of $\vec{u}_a$, leading to a non-zero $\alpha$ (Figure 1, right panel). Since the force between the balls during collision is applied at the point of contact, the direction of $\vec{v}_b$ ($\theta_{\vec{v}_b}$) is determined merely by the contact point angle $\alpha$, regardless of any other factors (note that $\theta_{\vec{u}_a}$ does not influence $\theta_{\vec{v}_b}$). The magnitude of $\vec{v}_b$, as well as the magnitude and direction of $\vec{v}_a$, further depend on the relative mass of the balls and the direction of $\vec{u}_a$. Figure 1 provides formulas for both the magnitudes and the directions of the two balls after the collision.

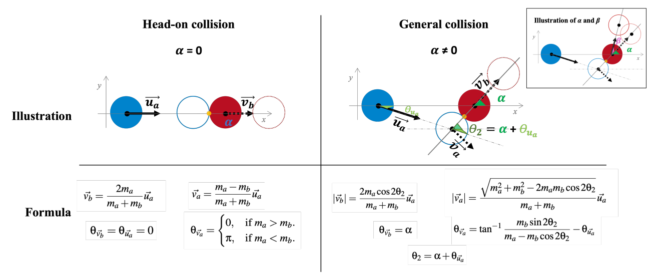


Figure 1: Illustration of the physics of launching events. Ball $a$ (blue) moves toward the stationary ball $b$ (red) with velocity $\vec{u}_a$. During collision, the line connecting the contact point and ball $b$'s center forms an angle $\alpha$ with the cardinal direction. After the collision, ball $b$ moves along $\vec{v}_b$ and ball $a$ moves along $\vec{v}_a$. Left panel: illustration and Newtonian formulas predicting the post-collision velocity magnitudes and directions of both balls in a head-on collision. Right panel: illustration and Newtonian formulas predicting the post-collision velocity magnitudes and directions of both balls in general elastic collisions. The top-right corner shows an illustration of $\alpha$ and $\beta$.

Unlike a head-on collision, it is physically plausible for ball $b$ to move in a direction that differs both from ball $a$'s initial velocity direction $\theta_{\vec{u}_a}$ and from the cardinal direction. In a physically plausible collision, $\alpha$ determines the direction of the target after collision: a larger $\alpha$ leads to a larger angle between ball $b$'s trajectory and the cardinal direction, whereas the trajectory of ball $b$ deviates less from the cardinal direction as $\alpha$ approaches $0°$.

## Participants

Nine participants (age range 21-27 years; 5 female, 3 male, 1 non-binary) took part in the experiments. All participants were students from Technical University of Darmstadt, including one author (LEK), two lab members, and six naive participants. They all had normal or corrected-to-normal vision and normal color vision. This study was approved by the ethics commission at the university (application number EK56/2022).

## Apparatus

Both experiments were conducted in a dimly lit room. A PROPixx projector (VPixx Technologies, Saint-Bruno, QC, Canada) was used to present visual stimuli in a cast area of 97 × 55 cm at a spatial resolution of 1920 × 1080 pixels and a refresh rate of 120 Hz. Participants were seated with their heads placed on a chin rest 130 cm from the screen, resulting in 47 pixels per degree of visual angle.

## Stimuli and procedure

Stimuli were similar to Michotte's launching display, in which a blue disk or ball (the "launcher") collided with an initially stationary red disk or ball (the "target"). Both balls had a radius of 40 pixels and matched luminance to mitigate contrast effects on perceived speed. Initially, the balls were aligned either horizontally (0°) or obliquely (45°), with the launcher positioned 508 pixels away from the target. The launcher moved at a speed of 16°/s (slow) or 48°/s (fast) toward the target. The specific spatial and temporal parameters were carefully chosen to ensure that the key frame of collision, in which the two balls contacted and formed a contact point angle $\alpha$, was displayed. The experiment was implemented in PsychoPy (version 2022.1.4, Peirce et al., 2019), and the balls' moving trajectories were implemented using the physics functions from the pooltool package (version 0.1.0, Kiefl, 2024).

**Angle judgment task** In the angle judgment task, participants watched the launching display up to the time point when the two balls made contact. They were then asked to use arrow keys to indicate whether the contact point was above or below the initial line of centers, where "up" or "left" indicated "above" and "down" or "right" indicated "below". After participants responded, feedback was provided via a fixation point that turned blue for correct responses and red for incorrect ones, displayed for 200 ms before the start of the next trial.

The experiment followed a blocked design, where speed (either slow or fast), orientation (either horizontal or oblique), and absolute contact point angle $|\alpha|$ did not vary from trial to trial within a block. The contact point angle $\alpha$ was randomly selected from [1.5°, 3.0°, 4.5°, 15.0°]. In each block of trials, there were equal numbers of above- and below- line of centers displays, and their order of presentation was randomized. The number of trials in each block varied, with most participants completing 60 or 80 trials per block (one informed participant completed as few as 6 trials in a block, while another completed as many as 120 trials). The order of the blocks was randomized. Participants completed a varied number of blocks depending on availability, resulting in different numbers of total trials (p1: 416, p2: 940, p3: 1356, p4: 1400, p5: 1560, p6: 1360, p7, p8, and p9: 1320).

**Causality judgment task** In the causality judgment task, participants watched the full launching display, with equivalent time length before and after collision. After collision, the target ball either moved towards the direction as predicted by Newtonian physics ($\alpha$), or toward a direction a certain angle offset away from this physically plausible condition ($\alpha \pm \beta$, where $\beta$ denotes the angle offset). Although it was physically implausible for the launcher to remain stationary after the collision (unless the two balls collided head-on and had equal mass), we decided to keep it stationary to maximize the chance that participants focused on the movement of the target. Participants were asked to indicate whether the blue ball caused the red ball to move (yes/no) using the keyboard. Similar to the angle judgment task, there was no time limit for responding, but in the causality judgment task participants did not receive feedback.

The experiment followed a blocked design, where speed (either slow or fast) and orientation (either horizontal or oblique) did not vary from trial to trial within a block. The contact point angle $\alpha$ was sampled from a normal distribution centered around the initial line of centers with a standard deviation of 5°, to ensure that the two balls collide in an almost head-on way with some variability. The additional post-collision angle offset $\beta$ was randomly selected from [1.5°, 3.0°, 4.5°, 15.0°, 30.0°, 60.0°], and had equal chance to be clockwise or counterclockwise away from the physically plausible direction. There were equal numbers of physically plausible and physically implausible displays in each block of trials, and their order of presentation was randomized. The order of the blocks was also randomized. Different angle offsets were interleaved within one block. Each block consisted of 240 trials. Each participant completed one block per condition, resulting in a total of 960 trials.

## Data analysis

Psychometric functions (cumulative Gaussian) were fitted separately for each participant's response data in the angle offset and causality judgment tasks. Following the notation of Schütt et al. (Schütt, Harmeling, Macke, & Wichmann, 2016):

$$P = \gamma + (1 - \gamma - \lambda)\Phi(x; m, w) \tag{3}$$

In this psychometric function (Eq. 3), $P$ denotes the probability of responding 'up' in the angle judgment task, and 'causal' in the causality judgment task. $\gamma$ denotes the guess rate, $\lambda$ denotes the lapse rate. The two parameters were set equal in the psychometric function fitting data from the angle judgment task, whereas this constraint was removed for the causality judgment task. $m$ indicates the threshold where the participant had equal chance of responding 'up' and 'down' (or 'causal' and 'not causal'), and $w$ indicates the width of the psychometric function. In the angle judgment task, the parameter $w$ of $\alpha$ is of central research interest: a larger $w$ indicates higher uncertainty and lower sensitivity to the perceptual input, while a smaller $w$ indicates lower uncertainty and better sensitivity ($w$ can be thought of as a measurement of the Just Noticeable Difference). For the causality judgment data, response data were combined for absolute angles, and the function was fitted to the negative half, while the visualization was flipped.

We fit the data with a mixed-effects model, assuming a binomial error distribution (in lme4-style notation: `response ~ psychometric_function(angle,` `parameters), parameters ~ orientation*speed + (orientation*speed | participants))`. The posterior distribution over model parameters was estimated using weakly-informative priors. The model posterior was estimated using MCMC implemented in the brms package (version 2.18.0, Bürkner, 2017) in the R environment. We computed four chains of 5000 steps, of which the first 2500 steps were used to tune the sampler.

# Results

## Within-subject effects across uncertainty manipulations

Figure 2 shows participants' performance for each condition. In the angle judgment task (column 1), participants correctly judged whether the contact point was above or below the line of centers as the contact point angle $\alpha$ increased. Despite notable individual differences, participants generally performed the best in the horizontal-slow condition (blue dot and solid line), and performed the worst in the oblique-fast (red triangle and dashed line) condition. In the causality judgment task (column 2), the probability of perceiving the launching event as causal decreased as the angle offset $\beta$ increased, suggesting that physical plausibility played an important role in subjective causality report. Causality reports were highest when the angle offset was small and in the oblique conditions. In contrast, the horizontal-slow condition was the least likely to elicit causal perception at small angle offsets ($\beta$). Moreover, in this condition, causal reports declined more slowly as $\beta$ increased, indicating relatively lower sensitivity to angle offset $\beta$ in causality judgments compared to the other conditions.

To better examine whether causality reports were influenced by uncertainty about the contact point angle $\alpha$, we fitted each participant's threshold of angle offset on causal report ($m_{causal}\beta$) as a function of contact point angle uncertainty ($w_{angle}\alpha$, Figure 2, column 3). The data aligned with the prediction of a Noisy Newton framework: the more uncertainty of $\alpha$, the more likely participants reported larger $\beta$ as causal. Linear regressions fitted to the data suggested a positive slope ($M = 2.16$, $SE = 0.76$, $t(8) = 3.01$, $p = 0.017$), suggesting that 1°increase of $w_{\alpha}$ led to an average increase of 2.16°shift of $m_{causal}\beta$. As for uncertainties, as $w_{angle}\alpha$ increased, the width of the causality report functions ($w_{causal}\beta$) tended to decrease, meaning that causal reports decreased more rapidly as $\beta$ increased (Figure 2, column 4). Linear regressions fitted to the data suggested a negative slope ($M = -1.16$, $SE = 0.20$, $t(8) = -6.24$, $p < 0.001$).

Marginalized effects of orientation and speed (Figure 3) show consistent patterns. Participants generally performed worse in the angle judgment task and tended to judge the event as causal in the oblique and fast conditions than in the horizontal and slow conditions, respectively. The associations between the psychometric function parameter estimates varied but most participants showed a pattern as predicted by a Noisy Newton model.

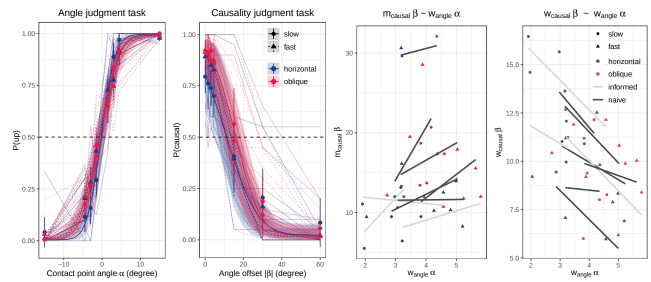


Figure 2: Performance in the angle judgment task (column 1) and causality judgment task (column 2). Faint lines link individual participant data, points show grand mean ± 2 SE over angles. Solid curves and shaded regions indicate mean and 95% credible regions of the a posterior distributions respectively. Column 3 shows fitted linear regressions of offset $\beta$ thresholds in causality reports ($m_{causal}\beta$) as a function of contact point angle uncertainty ($w_{angle}\alpha$), and column 4 fitted linear regressions of angle offset uncertainty in causality judgments ($w_{causal}\beta$) as a function of contact point angle uncertainty ($w_{angle}\alpha$).

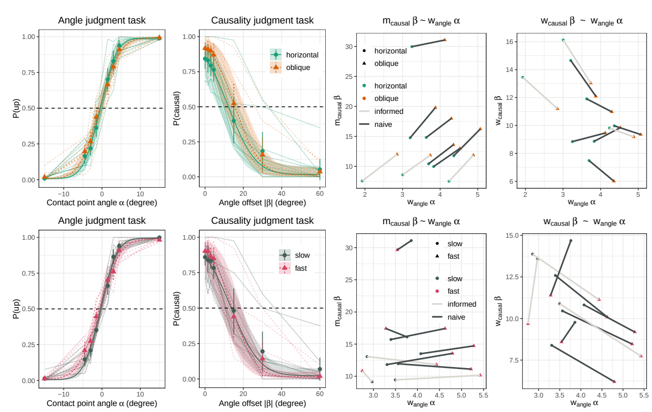


Figure 3: Performance marginalized on orientation (upper row) and speed (lower row). Legend same as in Figure 2.

## Between-subject effects across uncertainty manipulations

We examined whether the associations between psychometric function parameters observed at the individual level generalized across participants by plotting the fitted linear functions for each condition (Figure 4). Although none of the slope estimates reached statistical significance (our study was not powered to measure population-level associations), the pattern was generally consistent with the individual-level conclusions above. A positive association between $w_{angle}\alpha$ and $m_{causal}\beta$ was present in the slow conditions (slow-horizontal: $b = 2.81, SE = 4.23, t = 0.66, p = 0.53$; slow-oblique: $b = 7.95, SE = 4.33, t = 1.84, p = 0.11$) but not in the fast conditions (fast-horizontal: $b = -1.97, SE = 2.37, t = -0.83, p = 0.43$; fast-oblique: $b = -1.57, SE = 1.96, t = -0.80, p =$

45). Meanwhile, a negative association between $w_{angle}\alpha$ and $w_{causal}\beta$ was observed across all conditions (slow-horizontal: $b = -2.62, SE = 1.22, t = -2.15, p = 0.068$; slow-oblique: $b = -2.30, SE = 1.56, t = -1.48, p = 0.18$; fast-horizontal: $b = -0.58, SE = 0.74, t = -0.78, p = 0.46$; fast-oblique: $b = -0.65, SE = 0.62, t = -1.05, p = 0.33$).

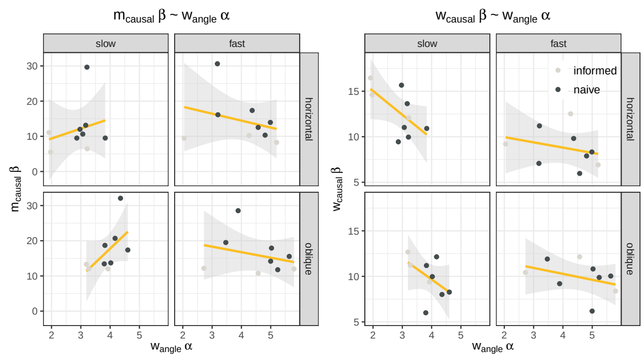


Figure 4: Associations between contact point angle uncertainty $w_{angle}\alpha$ and psychometric function parameters of angle offset $\beta$ on causality reports. Left panel: threshold of angle offset in causality judgments $m_{causal}\beta$. Right panel: sensitivity to angle offset in causality judgments $w_{causal}\beta$. Orange lines show the fitted linear function across individual participants' estimates (dots) for each condition.

## Discussion

In this study, we conducted two psychophysical experiments to measure participants' contact point angle ($\alpha$) judgments and their causality judgments in viewing launching displays with angle offsets ($\beta$). Similar to previous studies, we found that causality reports decreased as angle offsets increased, showing that causality inference was related to physical plausibility. Moreover, we observed that offset threshold of causality reports ($m_{causal}\beta$) increased as participants' uncertainty about the contact point angle increased (e.g. Figure 2, column 3), consistent with the idea of a mental physics model that relies on $\alpha$ to assess the physical plausibility of the launching event. We also observed that the sensitivity to angle offset in the causality judgment task ($w_{causal}\beta$) increased as uncertainty about the contact point angle increased (Figure 2, column 4). Though our study was not designed to measure associations at the population level, these patterns were generally consistent between individuals (Figure 4).

Our results generally agreed with the predictions of the Noisy Newton framework. As the two balls were guaranteed to make contact, and the time delay was always zero, our setting already created a strong prior for reporting causality (Sanborn et al., 2013; Shanks et al., 1989; Straube & Chatterjee, 2010). When perceptual input about $\alpha$ is noisy, while the Newtonian physics model is perfect, the likelihood distribution of the target ball's direction follows the same distribution as the perceived $\alpha$. Meanwhile, due to strong temporal cues and other contextual factors, it is highly likely to infer causality from the display, biasing the posterior probability toward reporting causality. However, the data we collected cannot distinguish whether the bias towards causality perception is due to the prior (e.g. a belief that temporally adjacent events are causally related) or due to inference of the visual scene based on an intuitive-physics model (e.g. estimated physical plausibility of the events based on an elastic collision model). Additional evaluation about an individual's general belief of causality could disentangle these possibilities.

Our results also suggested that factors beyond intuitive knowledge of Newtonian physics should be considered in explaining the individual differences in causality judgments (Smith & Vul, 2013; Smith, Battaglia, & Vul, 2018). Causality reports could be subjective and thus depend on one's knowledge about physics and the hypotheses of the experiment. Still, the manipulation of perceptual input noise yielded different perceptual and causal judgments, which could relate to different parameterization or beliefs in the internal physics model, or different strategies of attributing causality (Straube & Chatterjee, 2010). The manipulation of speed is particularly noteworthy: between-subject associations between $w_{angle}\alpha$ and $m_{causal}\beta$ seem to vary depending on display speed, suggesting that between-subject variation in causality judgments may be attributable to variation in participants' prior beliefs about velocity (e.g. participants may hold a non-Newtonian belief that fast-moving objects are more likely to be the cause of a collision; Kubricht et al., 2017). Additionally, since postdictive processing has been shown to play a role in causality reports (Bechlivanidis et al., 2022; Choi & Scholl, 2006; Deeb, Cesanek, & Domini, 2021), some of the configurations (e.g. oblique) may simply make it more difficult to visually detect deviations in the post-collision trajectory, which may also lead to increased causality rating in the corresponding configurations. Future studies should be conducted with a larger number of participants to better evaluate the individual differences. Additionally, rigorous computational models should be developed to simulate the process of causality judgment when viewing general collisions, taking into account both the directions and the magnitudes of the post-collision velocities.

In summary, we extended previous findings on the influence of spatial factors on physical plausibility and causality perception in launching displays to general, two-dimensional collision. Our results suggest that causality judgments generally align with predictions from the Noisy Newton framework, where people are more likely to perceive causality in displays that conform to Newtonian physics. The perception of the key factor that influences physical plausibility of the event, the contact point angle, also plays a role in causality judgments, and people rely more on other information sources when this perceptual input is noisy. Therefore, the perception of causality should be studied from both perceptual and cognitive perspectives.

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