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Pupil Dynamics and Causality Perception: Insights From Pupillometry

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ABSTRACT

Causality perception is fundamental to interpreting interactions between objects in the physical world. However, little is known about whether physiological responses, particularly pupil size, can implicitly track causality perception. This study employed pupillometry across three experiments to investigate the relationship between pupil dynamics and causality perception. The results revealed that spatiotemporally contiguous launching events (i.e., direct launching), perceived as a causal collision between two objects, induced greater pupil dilation after the collision than simple single-object motion (i.e., passing and pass-by events) or motion with a temporally inverted cause-effect order (i.e., temporal-inverted events), both of which lacked a causal structure. However, launching with a spatial gap (i.e., gap launching) also elicited pupil dilation comparable to direct launching, although gap launching was rated lower in perceived causality. Temporal-inverted events provoked early pupil dilation, corresponding to the sudden and spontaneous motion of the first object. Furthermore, for invariant visual stimuli that could be perceived as either causal launching or noncausal passing (i.e., ambiguous events), pupil size changes did not differentiate between subjective causal and noncausal judgments. These findings indicate that although pupil dilation was evident during causality perception, it was not uniquely or directly tied to causality perception but was influenced by multiple factors, particularly responses to spontaneous motion. This study deepens the understanding of the physiological mechanisms underlying causality perception while also emphasizing the limitation of using pupillometry to examine it.

1 | Introduction

The appreciation of cause and effect is essential for people to make sense of the world. Unlike causal reasoning, causality perception is an automatic and irresistible process that represents an immediate response to the physical or mechanical interactions of inanimate objects (Scholl and Tremoulet 2000). Imagine a scenario where two stationary objects, A and B, are lined up with a space between them; Object A (the launcher) starts moving toward Object B (the target) at a constant speed. Upon contact, Object A stops, and Object B starts moving in the same direction (Michotte 1963). This scenario illustrates a typical launching event in which Object A appears to cause Object B's motion by launching it. Causality perception in launching

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events has been shown to be influenced by certain spatiotemporal characteristics of the stimulus: temporal priority, temporal contiguity, and spatial contiguity (Hubbard 2013; Scholl and Tremoulet 2000; Young 1995). First, the launcher (the cause) should precede or at least occur simultaneously with the target (the effect). Second, the motion of the target should immediately start when the motion of the launcher stops. Third, there should be spatial contact between the final location of the launcher and the initial location of the target. A direct launching event that meets these three criteria generates the strongest impression of causality.

Numerous studies have reported weakened causality perception in launching events when a temporal delay or a spatial gap was introduced (Falmier and Young 2008; Guski and Troje 2003; Schlottmann and Anderson 1993; Schlottmann et al. 2006; Young and Falmier 2008; Young et al. 2005). In the gap condition, object A stopped moving before reaching a position adjacent to object B. In the delay condition, object B began moving after object A had stopped for a short period. Increasing the size of the gap and delay systematically reduced participants' causality ratings of whether object A caused object B's motion, with the highest ratings observed in the condition with no gap and no delay. For events with a moderate spatial gap but no temporal delay, participants reported intermediate levels of causality (Schlottmann et al. 2006; Young et al. 2005). This phenomenon, known as "launching at a distance", suggests that the launcher appears to influence the target's motion despite the presence of a spatial gap between them (Hubbard 2013).

Most research has relied on free verbal reports, structured response measures (e.g., ratings or forced choice) (Schlottmann et al. 2006), and psychophysical methods (Choi and Scholl 2006; Scholl and Nakayama 2004) to assess perceptual causality. Few studies have employed pupillometry to explore it. Pupillometry allows for continuous monitoring of physiological signals and provides precise temporal information. While pupil diameter typically changes in response to illumination, a process known as the pupillary light reflex, it is also modulated by arousal, attention, and cognitive processes (for a review, see Joshi and Gold 2020). For instance, pupil dilation has been linked to high memory load (Kahneman and Beatty 1966), great mental effort (Ahern and Beatty 1979), and decision uncertainty (Urai et al. 2017). Notably, even under constant physical luminance, pupil size was found to vary because of subjective experiences of brightness during visual illusions (Kinzuka et al. 2021; Laeng and Endestad 2012).

To our knowledge, only two studies have applied pupillometry to investigate causality perception (Adibpour and Hochmann 2023; Völter and Huber 2021). Using the violation of expectation (VOE) paradigm, these studies consistently revealed greater pupil dilation in the noncausal gap condition relative to the causal contact condition. Adibpour and Hochmann (2023) presented 8-month-old infants with 60% occluded and 40% unoccluded short movies. In occluded events, a yellow ball began moving from the left and went behind an occluder; shortly after it, a red ball that was initially positioned at the right boundary of and partly occluded by the occluder began moving rightward. In rare unoccluded events, the occluder was removed. The yellow ball stopped moving upon contacting the red ball or before contacting it, then the red ball started moving. Infants exhibited increased pupil dilation while watching the unoccluded events without contact compared to those with contact. Contrarily, another group of infants who only saw unoccluded movies did not show a significant difference in pupil diameter between contact and gap conditions. It suggested that infants' pupillary responses to rare unoccluded events were based on their interpretation of occluded events. They expected contact between the two balls behind the occluder and were surprised by the unoccluded events involving a gap. Völter and Huber (2021) examined pet dogs' expectations about contact causality and their sensitivity to violations of these expectations. They familiarized dogs with a single moving ball before testing them with launching events that either had or had no contact between two balls and uncovered that dogs had larger pupil diameter in the gap condition than in the contact condition.

In these studies, increased pupil dilation was attributable to violations of causality expectations. It implies that pupil dynamics may capture more about the expectation of causality than about the perception of causality itself. Previous research has also examined pupillary responses to violations of plausibility expectations. For example, Jackson and Sirois (2009) found that, after becoming familiar with plausible motion events, infants exhibited larger pupil dilation when watching impossible self-propelled motion events compared to possible equivalents. More broadly, these findings fit with evidence that pupil dilation reflects prediction error. In predication tasks (e.g., associative learning), pupil dilation increased when expected stimuli were omitted or unexpected stimuli were presented (Raisig et al. 2010; Zhang et al. 2019). Nevertheless, without triggering expectations, it remains unclear whether pupil dynamics inherently reflect causality perception. To address this question, we designed motion events that varied in temporal priority and spatial contiguity. These characteristics were shown to influence the intensity of perceived causality. We sought to determine whether differences in perceived causality are accompanied by differences in pupil dynamics.

Furthermore, to investigate whether pupil changes are directly linked to causality perception, we kept physical motion events constant and examined whether different pupil responses arose purely from subjective differences between causal and noncausal impressions. Rolfs et al. (2013) created an ambiguous event that can be perceived equally as a causal launch or a noncausal pass. This ambiguous event was similar to a direct launch but involved a moderate spatial overlap between the launcher and the target, where a 0% overlap event was reliably perceived as a causal launch and a 100% overlap event was often perceived as a noncausal pass. Few studies have explored pupil dynamics during viewing of physically invariant but ambiguous stimuli. Kloosterman et al. (2015) focused on motion-induced blindness (MIB), a phenomenon where a salient target surrounded by a moving mask disappears from visual awareness and then reappears. They found that the subjective experience of target disappearance elicited larger pupil dilation than the subjective experience of target reappearance. Sato et al. (2020) observed that perceiving an ambiguous Necker cube from below induced greater pupil

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dilation compared to perceiving it from above. These findings suggest that different perceptual experiences that may stem from different cognitive processes could be detected through pupil responses, although the physical stimuli remained constant.

We conducted three experiments in this study. In Experiment 1, four types of motion events were presented: direct launching, gap launching, passing, and pass-by events. Pupillometry data and causality ratings were collected in separate sessions. Based on previous studies (Rolfs et al. 2013; Schlottmann et al. 2006; Young et al. 2005), we expected the highest causality ratings for direct launching events, followed by gap launching events, and the lowest for passing and pass-by events that featured a single moving object. If pupillary responses reflect perceptual causality, changes in pupil diameter should align with the pattern of causality ratings and distinguish causal from noncausal events. Experiment 2 was to replicate the findings of Experiment 1 while replacing passing events with temporally inverted events. This condition depicted a completely noncausal interaction, in which object B moved first and object A moved immediately after object B stopped. Hence, this animation lacked both temporal priority and spatial contiguity, although it retained temporal contiguity (Young et al. 2005). In Experiment 3, participants watched three types of motion events: direct launching, passing, and ambiguous events. Participants judged causal relations during pupillary recording. The ambiguous condition was of primary interest among the three conditions. We classified trials judged as causal launching and noncausal passing and compared pupil responses between these two types of judgments. If pupil dynamics directly relate to causality perception, subjective causal and noncausal judgments could be differentiated through pupil responses.

2 | Method

2.1 | Participants

A total of 78 participants took part in this study. Twenty-four participated in Experiment 1 (12 females; mean age ± SD = 23.4 ± 2.6 years), 28 in Experiment 2 (15 females; 22.6 ± 2.6 years), and 26 in Experiment 3 (16 females; 22.6 ± 2.3 years). All participants had normal or corrected-to-normal vision and gave written informed consent in accordance with procedures and protocols approved by the institutional review board of the Institute of Psychology, Chinese Academy of Sciences. They were all naïve to the purpose of the experiment.

2.2 | Apparatus

Stimuli were generated and displayed using MATLAB (Mathworks Inc., Natick, MA) together with the Psychophysics Toolbox extensions (Brainard 1997; Pelli 1997) on an Alienware 2310 monitor (1680 × 1050 at 60 Hz). Participants were seated 60 cm in front of the screen with their heads on a chin-rest and were told to minimize head movements during the experiments. Pupil size (area) of the right eye was recorded using Eyelink Portable Duo (SR Research, Canada) at 1000 Hz. The recorded pupil size was analyzed and reported in arbitrary units (a.u.). To convert the pupil data from arbitrary units to diameter, multiply the square root of the pupil data by the scaling factor (0.106).

2.3 | Stimuli

All stimuli were presented on a gray background (luminance: 16 cd/m^2), with two black regions (luminance: 0.2 cd/m^2) positioned at the top and bottom of the display respectively. Animations consisted of two black (luminance: 0.2 cd/m^2) discs (A and B), each extending 1.3° of visual angle. The discs each moved for 600 ms at a speed of 18°/sec, consecutively in the same direction. The starting position of one disc was hidden by the bottom black region and the stopping position of the other disc was hidden by the top black region. The angle between the moving trajectory and the horizontal axis was set at 30°.

Experiment 1 included four conditions: direct launching, gap launching, passing, and pass-by events (Figure 1A). In direct launching events, disc A moved from the bottom black region until it was adjacent to disc B, and disc B began moving immediately in the same direction until it disappeared behind the top black region. Gap launching and passing events were similar to direct launching events except for different spatial relationships between the two discs. In passing events, disc A completely overlapped with disc B when it stopped. In gap launching events, disc A stopped moving when it reached the same vertical position as disc B, with a 3° horizontal distance between them. Lastly, in pass-by events, disc A maintained a 3° horizontal distance from disc B while passing through it and continued moving until it disappeared behind the top black region. Disc B remained stationary throughout.

Experiment 2 replaced the passing events in Experiment 1 with temporal-inverted events (Figure 1A), while retaining the other three event types. In temporal-inverted events, disc B moved first and disappeared behind the top black region; then disc A moved from the bottom black region and stopped 3° horizontally from disc B's initial position.

Experiment 3 involved three conditions of overlap between disc A and disc B: 0%, 100%, and an ambiguous level. The 0% overlap and 100% overlap conditions were identical to the direct launching and passing events of Experiment 1. The overlap in the ambiguous condition was individually determined in a behavioral pilot test, depending on each participant's point of subjective equality (PSE) in evaluating animations with nine degrees of overlap (0%–100%, in steps of 12.5%) (Kominsky and Scholl 2020; Rolfs et al. 2013) (Figure 1B). The PSE, defined as the point at which participants gave 50% judgments as passing in terms of the overlap degree, was derived by fitting the proportion of passing judgments to a Boltzmann sigmoid function ($f(x) = 1 / \left(1 + \exp\left(\left(x - x_0\right) / \omega\right)\right)$). The variation in overlap was achieved by adjusting the starting location of disc A according to the location of disc B so that the duration and speed of the two discs were constant across all trials.

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2.4 | Procedure

In Experiment 1, each trial began with a nine-point eye-tracker calibration, followed by a black cross (1°×1°) presented at the center of the screen for a variable duration (500–1000 ms). A black disc (disc B) was positioned horizontally aligned with the central cross, either on the left or right side of the screen, jittered within 4.5°–5° of the center. At the same time, the second black disc (disc A) appeared near the left or right bottom corner of the screen and was occluded by the bottom black region, rendering it invisible to participants. In three conditions (direct launching, gap launching, and passing events), the animation began when disc A started moving and ended when disc B stopped behind the top black region. In the pass-by condition, the animation illustrated a single motion of disc A. On each trial, participants viewed an animation from one of the four conditions. After the animation ended, the discs remained on the screen for 1000 ms, and then participants made a judgment by pressing one of four keys ("D", "F", "J", "K") to indicate which of the four motion events the animation illustrated. The intertrial interval was set as 2000 ms, during which a blank screen was shown (Figure 2). There were 240 trials in total, with 60 trials in each of the four

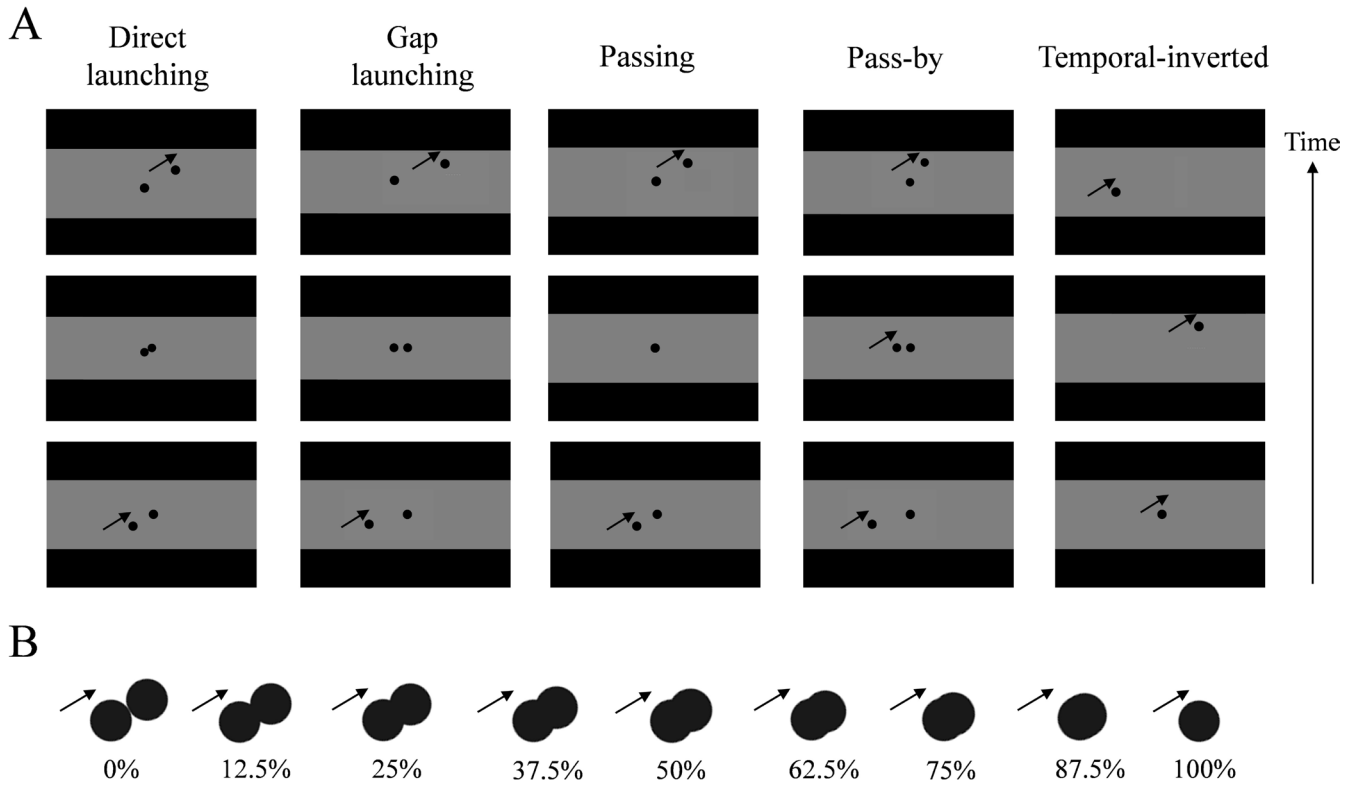

FIGURE 1 | (A) Schematic representation of the experimental conditions. Experiment 1 included direct launching, gap launching, passing, and pass-by events; Experiment 2 included direct launching, gap launching, pass-by, and temporal-inverted events. (B) The behavioral pilot test of Experiment 3 used nine degrees of overlap (0%–100%, in steps of 12.5%).

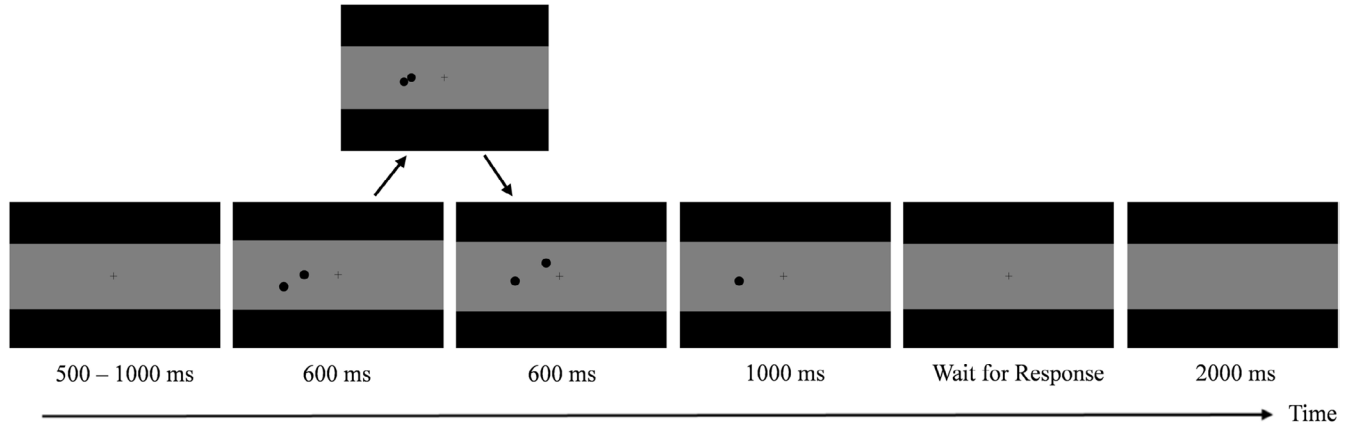

FIGURE 2 | Schematic representation of the experimental procedure. In Experiment 1, participants viewed four types of motion events: direct launching, gap launching, passing, and pass-by events. They were required to judge which of the four events was depicted in the animation. An example trial of a direct launching event was shown.

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conditions. The presentation of trials was fully randomized. The assignment of the keys was counterbalanced across participants. Participants were instructed to fixate on the central cross throughout the experiment and keep their heads as still as possible. After completing the eye-tracking session, participants rated all four types of motion events on a nine-point Likert scale to indicate the extent to which they perceived disc A caused disc B to move (1 = not at all, 9 = absolutely).

The procedure of Experiment 2 was almost identical to that of Experiment 1, differing only in the presentation of temporal-inverted events.

The procedure of Experiment 3 was similar to that of Experiment 1 but differed in the stimuli used and the judgments required. Animations were from the three overlap conditions (0%, 100%, and the ambiguous overlap). After each animation ended and the discs disappeared, participants made a launch or a pass judgment by pressing one of two keys ("F" or "J"). There were 240 trials in total: 60 in the 0% overlap (direct launching) condition, 60 in the 100% overlap (passing) condition, and 120 in the ambiguous condition. The trials were presented in a pseudo-random order, with no condition appearing more than three times consecutively. The indication of the keys was counterbalanced across participants.

2.5 | Data Processing

Continuous pupil data were first segmented into epochs from −200 to 2200 ms, locked to the time when the discs were displayed (i.e., stimulus onset). Individual pupil size data in each trial were then preprocessed to remove eye blinks and other artifacts. Data points that were lost due to recording errors, dropped to zero because of blinks, or deviated 3 standard deviations from the mean pupil size were identified for interpolation. Trials in which identified data points requiring interpolation took up more than 30% of the baseline period and stimuli display time (2400 ms in total) were discarded. The remaining trials were linearly interpolated. Then all trials were visually inspected, and trials with recognizable artifacts (e.g., remaining blink artifacts) were excluded. Finally, the pupil size data were baseline-corrected for each trial by subtracting the mean pupil size during the 200 ms pre-stimulus period.

In Experiment 1, an average of 1.00 trial was excluded in the direct launching condition, 1.21 trials in the gap launching condition, 1.04 trials in the passing condition, and 1.17 trials in the pass-by condition. In Experiment 2, an average of 1.89 trials were excluded in the direct launching condition, 2.29 trials in the gap launching condition, 2.04 trials in the temporal-inverted condition, and 2.07 trials in the pass-by condition. In Experiment 3, 2.42 trials were excluded in the direct launching condition, 2.04 trials in the passing condition, 2.42 trials in the launching perceived ambiguous condition, and 2.92 trials in the passing perceived ambiguous condition.

After preprocessing, consecutive paired-sample t-tests were conducted at each time point from 200 ms before stimuli onset to 2200 ms after stimuli onset across all three experiments. In Experiments 1 and 2, pairwise comparisons were performed across all conditions. In Experiment 3, the tests focused on pupil size differences between the direct launching and passing conditions, driven either by physical stimuli or by subjective judgments. To address the issue of multiple comparisons over time, cluster-based permutation analysis was employed (Groppe et al. 2011).

To examine differences in perceived causality across the four conditions in Experiments 1 and 2, we conducted repeated-measures ANOVAs on the causality ratings. Significant results were followed by post hoc pairwise comparisons with Bonferroni correction.

3 | Results

3.1 | Experiment 1

Participants showed high accuracy in differentiating among the four types of animations. The mean accuracy was 0.95 (SD = 0.06) for the direct launching condition, 0.95 (SD = 0.07) for the gap launching condition, and 0.98 (SD = 0.02) for both the passing and pass-by conditions.

For the pupillometry results (Figure 3A), the direct launching condition elicited greater pupil dilation than the passing condition from 1637 to 2200 ms and the pass-by condition from 1204 to 2200 ms. Similarly, the gap launching condition induced larger pupil dilation than the passing condition from 1599 to 2200 ms and the pass-by condition from 1247 to 2200 ms. All significant periods occurred after the animation ended. No other significant differences in pupil size were observed across conditions.

For the rating results (Figure 3B), a repeated-measures ANOVA revealed a significant main effect of conditions, $F(1.48, 34.12) = 142.64$, $p < 0.001$, $\eta_p^2 = 0.86$. Post hoc tests showed significant differences for all pairwise comparisons ($ps < 0.001$), except for the comparison between the passing and pass-by conditions ($p = 1.00$). Descriptive statistics showed the highest causality ratings in the direct launching condition ($M = 8.58$, SD = 0.61), moderate ratings in the gap launching condition ($M = 4.27$, SD = 2.44), and the lowest ratings in the passing ($M = 1.54$, SD = 1.07) and pass-by ($M = 1.10$, SD = 0.51) conditions.

In Experiment 1, we demonstrated that pupil size changes were associated with causality perception, with greater pupil dilation and the highest causality ratings in the direct launching condition. However, pupil dilation did not distinguish between the direct launching and gap launching conditions, despite significant differences in causality ratings. The gap launching events basically featured the sudden stop of the first object and the sudden onset of the second object without external force, which was referred to as self-propelled motion in Di Giorgio et al. (2017). It is unclear whether the observed pupil dilation was also attributable to self-propelled motion rather than exclusively linked to causality perception. Therefore, we conducted Experiment 2. It included a temporal-inverted condition where the motion order of the two objects was temporally swapped. The original target object initially and spontaneously moved, and the original launcher followed it. If self-propelled motion

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plays a role, this condition should produce early pupil dilation during the spontaneous motion of the first object. We retained the direct launching, gap launching, and pass-by conditions to replicate the results of Experiment 1. Similar to pass-by events, temporal-inverted events lacked causal interactions. Thus, differences in pupil dynamics were expected between the temporal-inverted and direct launching conditions.

3.2 | Experiment 2

Participants also demonstrated superior performance in distinguishing among the four conditions. The mean accuracy was 0.96 (SD = 0.04) for the direct launching condition, 0.93 (SD = 0.10) for the gap launching condition, 0.98 (SD = 0.05) for the temporal-inverted condition, and 0.97 (SD = 0.06) for the pass-by condition.

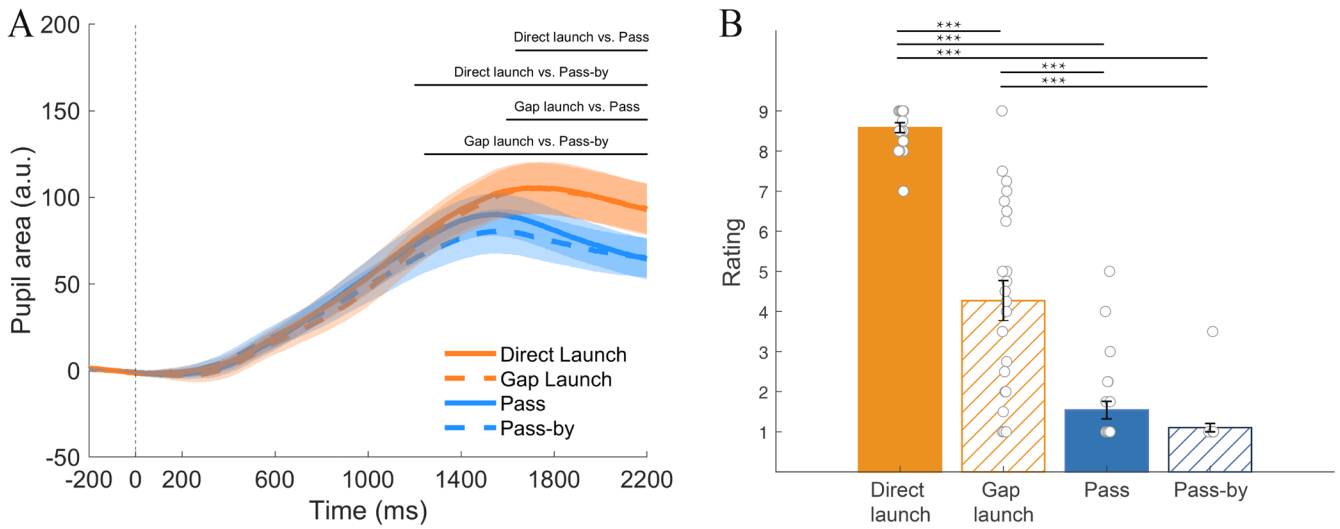

FIGURE 3 | Results from Experiment 1. (A) Pupillometry results. Solid or dashed lines represent pupil area data under different conditions as a function of time; shaded areas represent the standard error (SE) between participants; horizontal thin black lines indicate significant differences after cluster-based permutation correction ($p < 0.05$). All the pupil data are in arbitrary units (a.u.). (B) Rating results. Ratings were measured on a 1–9 scale, indicating the extent to which participants perceived disc A caused disc B to move (1 = not at all, 9 = absolutely). Individual data points were shown as scatter dots. Error bars represent standard errors of the mean. ***$p < 0.001$ indicates significant differences between conditions as determined by post hoc tests.

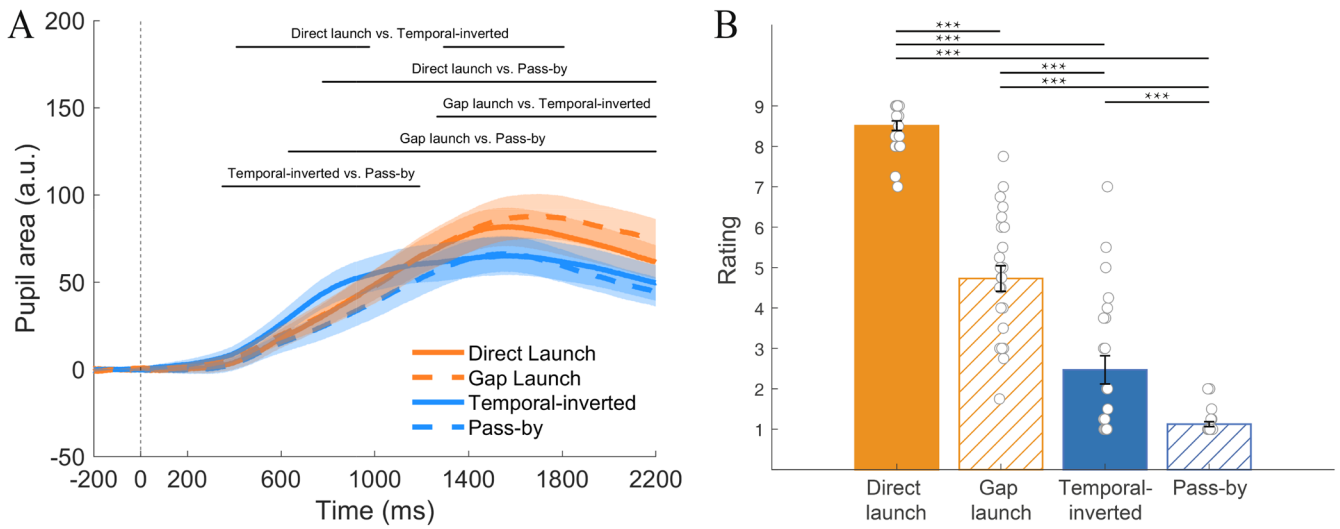

FIGURE 4 | Results from Experiment 2. (A) Pupillometry results. Solid or dashed lines represent pupil area data under different conditions as a function of time; shaded areas represent the standard error (SE) between participants; horizontal thin black lines indicate significant differences after cluster-based permutation correction ($p < 0.05$). All the pupil data are in arbitrary units (a.u.). (B) Rating results. Ratings were measured on a 1–9 scale, indicating the extent to which participants perceived disc A caused disc B to move (1 = not at all, 9 = absolutely). Individual data points were shown as scatter dots. Error bars represent standard errors (SE) of the mean. ***$p < 0.001$ indicates significant differences between conditions as determined by post hoc tests.

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The pupillometry results (Figure 4A) showed that both the direct launching and gap launching conditions induced greater pupil dilation during late time periods compared to the temporal-inverted condition (direct launching, 1295–1807 ms; gap launching, 1268–2200 ms) and the pass-by condition (direct launching, 779–2200 ms; gap launching, 634–2200 ms). Additionally, during early time periods, the temporal-inverted condition produced significantly greater pupil dilation than the direct launching condition (410–977 ms) and the pass-by condition (350–1192 ms). No other significant differences in pupil size were observed across conditions.

For the rating results (Figure 4B), a repeated-measures ANOVA revealed a significant main effect of experimental conditions, $F(2,\ 53.99) = 208.32$, $p < 0.001$, $\eta_p^2 = 0.89$. Post hoc analyses showed significant differences between all conditions ($ps < 0.001$). Descriptive statistics indicated the highest causality ratings in the direct launching condition ($M = 8.53$, SD = 0.60), followed by the gap launching ($M = 4.86$, SD = 1.66), temporal-inverted ($M = 2.44$, SD = 1.67), and pass-by conditions ($M = 1.14$, SD = 0.32).

In Experiment 2, we consistently observed significant pupil dilation and the strongest causality ratings in the direct launching condition compared to the pass-by and temporal-inverted conditions. The gap launching condition again induced pupil dilation indistinguishable from that in the direct launching condition, although receiving lower causality ratings. Intriguingly, the temporal-inverted condition provoked significant pupil dilation early during the sudden and spontaneous motion of the first object. The findings suggest that both causality perception and self-propelled motion may contribute to the observed pupil dilation. To further investigate whether pupil dynamics purely reflect causality perception when all other potential factors are controlled, we conducted Experiment 3. It introduced an ambiguous condition, where the visual motion events were manipulated as constant but could be judged as either causal launching or noncausal passing. If pupil dynamics are inherently sensitive to causality perception, distinct responses should emerge between subjective causal and noncausal judgments.

3.3 | Experiment 3

Figure 5A shows a fitted curve depicting the proportion of passing reports as a function of the overlap degree. The mean proportions of passing reports for three conditions (i.e., direct launching, ambiguous, passing) were calculated (Figure 5B). Participants gave the fewest passing reports ($M = 0.06$, SD = 0.06) in the 0% overlap trials (i.e., direct launching condition) and the most ($M = 0.98$, SE = 0.03) in the 100% overlap trials (i.e., passing condition). In the ambiguous condition, passing judgments were moderate ($M = 0.55$, SE = 0.12), indicating that participants judged nearly half of the trials as passing and the other half as direct launching.

Pupillometry findings revealed significantly larger pupil dilation in the direct launching condition than in the passing condition between 1203 and 2200 ms (Figure 5C), replicating the observations of Experiment 1. However, in the ambiguous condition, where the physical animations were identical, no significant differences in pupil dilation were observed between causal launch and noncausal pass judgments. It suggests that pupil responses were not sensitive to subjective differences in causality judgments. Notice that pupil size in both launching and passing conditions in Experiment 3 was larger than in Experiment 1, which may be due to differences in task difficulty. Experiment 1 included unambiguous launching and passing events, whereas Experiment 3 presented both unambiguous and ambiguous trials. Participants likely found Experiment 3 more difficult overall, and therefore showed enhanced pupil dilation (e.g., Alnæs et al. 2014).

4 | Discussion

This study represents the first attempt to directly investigate the relationship between pupil dynamics and causality perception in healthy human adults, enriching our understanding of the physiological mechanisms underlying causality perception. The findings revealed different pupil dynamics during the perception of visual motion events with varied spatiotemporal characteristics. In line with our predictions, Experiments 1 and 2 showed that direct launching and gap launching events evoked greater pupil dilation than passing, pass-by, and temporal-inverted events from the motion of the second object to judgment making. Unexpectedly, we did not observe significant differences in pupil changes between direct launching and gap launching conditions. Regarding behavioral causality ratings, our observations were largely consistent with previous studies (Schlottmann et al. 2006; Young et al. 2005): perceived causality was highest in the direct launching condition, intermediate in the gap launching condition, lower in the temporally inverted condition, and lowest in the passing and pass-by conditions.

Contrary to our pupillary findings, previous studies (Adibpour and Hochmann 2023; Völter and Huber 2021) showed that the gap launching condition induced larger pupil dilation compared to the direct (contact) launching condition. This discrepancy could be attributed to differences in purpose and design. Previous studies used the violation of expectation (VOE) paradigm to investigate whether infants and dogs understand physical causality. In a typical VOE task, infants are familiarized with an event before being presented with similar events that may or may not violate certain physical principles. Longer looking time or larger pupil dilation to impossible events signals infants' detection of violations of these principles, thereby revealing their grasp of such knowledge (Jackson and Sirois 2022). Adibpour and Hochmann (2023) familiarized infants with occluded events and tested them with rare unoccluded events involving either a gap or contact. If infants expected contact between the two objects behind the occluder, they would be surprised when watching unoccluded gap events, as reflected in increased pupil dilation. Similar to VOE, earlier studies using the habituation paradigm have also uncovered infants' understanding of causal relations (e.g., Cohen and Amsel 1998; Kominsky et al. 2017; Saxe and Carey 2006). Six-month-old infants looked longer at gap or delay events after being habituated to contact launching events; they also looked longer at contact launching events after being habituated to gap or delay events (Cohen and Amsel 1998). Both VOE and habituation paradigms have been used extensively to examine the presence of cognitive abilities in preverbal

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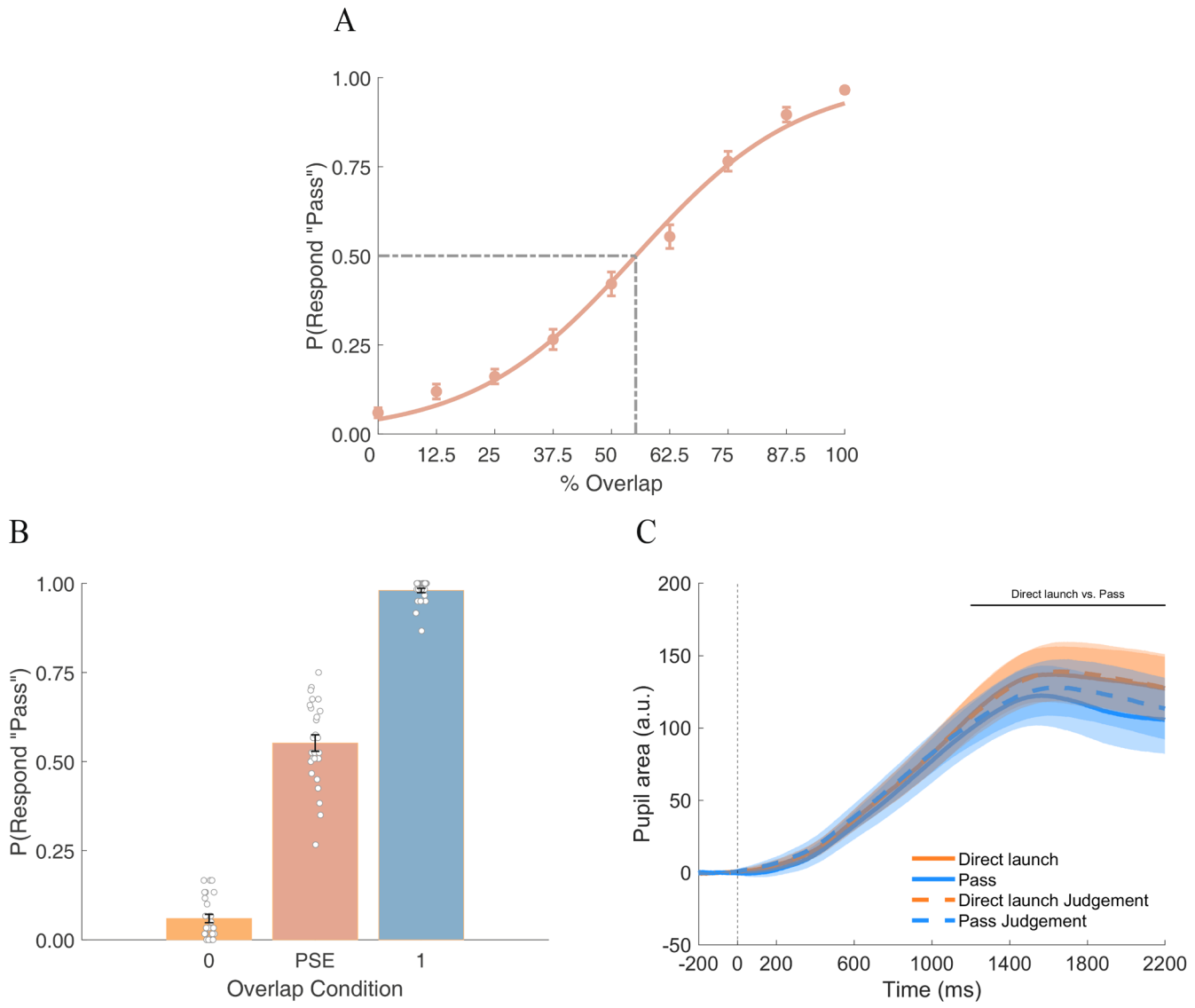

FIGURE 5 | Results from Experiment 3. (A) The proportion of responses in which participants gave passing reports, plotted as a function of the degree of overlap between the two discs. (B) Participants gave the fewest passing reports in the direct launching condition and the most in the passing condition. In the ambiguous condition, passing judgments were moderate. Individual data points were shown as scatter dots. Error bars indicate standard errors (SE) of the mean. (C) Pupillometry results. Solid or dashed lines represent pupil area data under different conditions as a function of time; shaded areas represent the SE between participants; horizontal thin black lines indicate significant differences after cluster-based permutation correction ($p < 0.05$). All the pupil data are in arbitrary units (a.u.).

infants (Baillargeon 2004). In contrast, the present study aimed to explore real-time physiological signals accompanying adults' perception of causality. Without prompting any expectations, we directly tested adults' pupillary responses to causal versus noncausal motion events.

In our study, the enhanced pupil dilation observed during launching events (even with a spatial gap) likely reflects heightened attention and engagement in causality perception. Several eye-tracking studies have shown that causality perception biases observers' eye movements and suggest attention as a potential mechanism. Badler et al. (2010) measured adults' eye movement responses to tool events, where a launcher contacted a tool that in turn triggered the motion of a reaction target. The reaction target could move either in a causal (i.e., along the same trajectory as the launcher) or in a noncausal (i.e., deviated from the trajectory of the launcher) direction, with equal probability. Participants were instructed to track the target following a collision. The findings showed that participants exhibited significantly more smooth pursuit and saccades as well as shorter pursuit latencies toward the causal direction relative to the noncausal direction. This bias was absent in control events with temporal delays or spatial gaps. Thus, it was concluded that causality perception can modulate eye movements, probably because the inference of a causal relation enhances attention toward a putative causal target and subsequently influences eye movements (Badler et al. 2010). Mascalzoni et al. (2013) examined newborns' fixation while viewing two bilaterally animated sequences: one depicting a direct launching event with causal interaction and the other showing a noncausal motion event featuring either a delay or a temporally inverted sequence. Newborns were found to fixate longer on the direct launching events compared to the delay

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or inverted events. This study suggests that newborns, only a few hours old and without prior visual experience, already displayed preferential attention to causal motion events.

However, it is noteworthy that increased pupil dilation in the gap launching condition may also result from the unexpected sudden stop of the launcher, the unexpected sudden start of the target, or both. Similarly, the temporally inverted condition was found to induce larger pupil dilation than the direct launching and pass-by conditions after the abrupt start of the first object. This object spontaneously set out from the center of the screen, with its initial motion visible to the observers. Consequently, in both gap launching and temporally inverted events, observers may feel surprised that an inert object moved or stopped spontaneously without the application of external force. Indeed, self-propelled motion is a critical cue of animacy. There is evidence that infants are sensitive to this cue and could differentiate animate from inanimate objects based on it. In an eye-tracking study, newborns were presented with two bilateral motion events (i.e., self-propelled and non-self-propelled). In the self-propelled motion event, the object started from rest with its onset motion visible, whereas in the non-self-propelled motion event, the object moved out from an occluder so that its onset motion was unavailable. The results showed that newborns fixated longer in the self-propelled condition compared to the non-self-propelled condition (Di Giorgio et al. 2017). Therefore, it is likely that both causality perception and animacy perception influenced pupillary responses in the current study, and the observed pupil dilation may not reflect causality perception alone.

In addition, in Experiments 1 and 2, the patterns of pupil dynamics did not align with the patterns of causality ratings across experimental conditions; this discrepancy may also lie in the fact that pupil changes were driven not solely by causality perception but by multiple factors. Previous research has also revealed a divergence between perceptual judgments and eye movements in processing visual motion events (Badler et al. 2012; Yoshimoto and Hayasaka 2022). Badler et al. (2012) compared adult participants' oculomotor and psychophysical responses to tool events, in which the target moved either in a causal or in a noncausal direction. Participants first completed an oculomotor task, during which they fixated on the target and tracked it when it began to move. In a subsequent psychophysics task, they viewed the same stimuli and made causal or noncausal judgments. The findings showed that both oculomotor and psychophysical responses tended to bias toward the causal direction. However, no strong correlation was found between psychophysical response latency and eye movement direction or latency. When stimulus complexity was increased by introducing a time delay in half of the trials, the divergence between these two responses became more pronounced. Oculomotor responses maintained the causal bias, while psychophysical responses became more variable, potentially influenced by individual experience.

Lastly, in Experiment 3, we failed to observe significant differences in pupil dynamics between subjective causal and noncausal judgments. This indicates that when the physical motion events remained unchanged, the subjective perception of causality did not modulate pupil responses. While studies on ambiguous perception of motion-induced blindness (MIB; Kloosterman et al. 2015) and the Necker cube (Sato et al. 2020) showed different pupil responses to distinct subjective percepts of invariant visual stimuli, null results were reported in an fMRI study focusing on the neural basis of causality perception (Straube and Chatterjee 2010). This study created launching animations with varying moving angles (0°, 7.5°, 15°, 22.5°, 30°, 45°, 60°) and time delays (0, 33, 67, 100, 133, 200, 267 ms) between the involved objects. During fMRI scanning, participants judged whether object A caused object B to move. Based on their causal or noncausal judgments, the trials were classified into two groups. The results showed nonsignificant differences in brain activation between the two groups. These null effects further challenge the possibility of a direct link between causality perception and pupil dynamics.

In conclusion, our study revealed that direct launching events, which depicted a causal collision between two objects, elicited greater pupil dilation after the collision compared to noncausal events, namely single-object motion and motion with a temporally inverted cause-effect order. This increased pupil dilation likely reflects heightened attention and engagement during causality perception. However, it cannot be solely attributed to causality perception, as launching with a spatial gap induced comparable pupil dilation to direct launching despite having lower causality ratings. Additionally, temporally inverted events produced early pupil dilation during the sudden and spontaneous motion of the first object. Moreover, pupil size changes did not reflect differences between subjective causal and noncausal judgments when visual stimuli remained constant. These findings suggest that while pupil dilation accompanies causality perception, it is not uniquely sensitive to it. The utility of pupillometry in studying causality perception appears limited, primarily due to the challenge of disentangling multiple contributing factors.

Author Contributions

Miao Zhong: data curation, formal analysis, methodology, visualization, writing – original draft, writing – review and editing. **Yiwen Yu:** data curation, formal analysis, investigation, visualization, writing – original draft, writing – review and editing. **Shiqi Tan:** investigation, writing – review and editing. **Xiangyong Yuan:** funding acquisition, methodology, supervision, writing – review and editing. **Yi Jiang:** conceptualization, funding acquisition, methodology, supervision, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All data and code in this study is available from Psychological Science Bank (https://www.scidb.cn/en/s/rMFVbi).

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References

Adibpour, P., and J.-R. Hochmann. 2023. "Infants' Understanding of the Causal Power of Agents and Tools." *Proceedings of the National Academy of Sciences* 120, no. 50: e2309669120. https://doi.org/10.1073/pnas.2309669120.

Ahern, S., and J. Beatty. 1979. "Pupillary Responses During Information Processing Vary With Scholastic Aptitude Test Scores." *Science* 205, no. 4412: 1289–1292. https://doi.org/10.1126/science.472746.

Alnæs, D., M. H. Sneve, T. Espeseth, T. Endestad, S. H. P. van de Pavert, and B. Laeng. 2014. "Pupil Size Signals Mental Effort Deployed During Multiple Object Tracking and Predicts Brain Activity in the Dorsal Attention Network and the Locus Coeruleus." *Journal of Vision* 14, no. 4: 1–20. https://doi.org/10.1167/14.4.1.

Badler, J., P. Lefevre, and M. Missal. 2010. "Causality Attribution Biases Oculomotor Responses." *Journal of Neuroscience* 30, no. 31: 10517–10525. https://doi.org/10.1523/JNEUROSCI.1733-10.2010.

Badler, J. B., P. Lefèvre, and M. Missal. 2012. "Divergence Between Oculomotor and Perceptual Causality." *Journal of Vision* 12, no. 5: 1–15. https://doi.org/10.1167/12.5.3.

Baillargeon, R. 2004. "Infants' Physical World." *Current Directions in Psychological Science* 13, no. 3: 89–94. https://doi.org/10.1111/j.0963-7214.2004.00281.x.

Brainard, D. H. 1997. "The Psychophysics Toolbox." *Spatial Vision* 10, no. 4: 433–436. https://doi.org/10.1163/156856897X00357.

Choi, H., and B. J. Scholl. 2006. "Measuring Causal Perception: Connections to Representational Momentum?" *Acta Psychologica* 123, no. 1: 91–111. https://doi.org/10.1016/j.actpsy.2006.06.001.

Cohen, L. B., and G. Amsel. 1998. "Precursors to Infants' Perception of the Causality of a Simple Event." *Infant Behavior and Development* 21, no. 4: 713–731. https://doi.org/10.1016/S0163-6383(98)90040-6.

Di Giorgio, E., M. Lunghi, F. Simion, and G. Vallortigara. 2017. "Visual Cues of Motion That Trigger Animacy Perception at Birth: The Case of Self-Propulsion." *Developmental Science* 20, no. 4: e12394. https://doi.org/10.1111/desc.12394.

Falmier, O., and M. E. Young. 2008. "The Impact of Object Animacy on the Appraisal of Causality." *American Journal of Psychology* 121, no. 3: 473–500. https://doi.org/10.2307/20445477.

Groppe, D. M., T. P. Urbach, and M. Kutas. 2011. "Mass Univariate Analysis of Event-Related Brain Potentials/Fields I: A Critical Tutorial Review." *Psychophysiology* 48, no. 12: 1711–1725. https://doi.org/10.1111/j.1469-8986.2011.01273.x.

Guski, R., and N. F. Troje. 2003. "Audiovisual Phenomenal Causality." *Perception & Psychophysics* 65, no. 5: 789–800. https://doi.org/10.3758/BF03194815.

Hubbard, T. L. 2013. "Phenomenal Causality I: Varieties and Variables." *Axiomathes* 23, no. 1: 1–42. https://doi.org/10.1007/s10516-012-9198-8.

Jackson, I., and S. Sirois. 2009. "Infant Cognition: Going Full Factorial With Pupil Dilation." *Developmental Science* 12, no. 4: 670–679. https://doi.org/10.1111/j.1467-7687.2008.00805.x.

Jackson, I. R., and S. Sirois. 2022. "But That's Possible! Infants, Pupils, and Impossible Events." *Infant Behavior & Development* 67: 101710. https://doi.org/10.1016/j.infbeh.2022.101710.

Joshi, S., and J. I. Gold. 2020. "Pupil Size as a Window on Neural Substrates of Cognition." *Trends in Cognitive Sciences* 24, no. 6: 466–480. https://doi.org/10.1016/j.tics.2020.03.005.

Kahneman, D., and J. Beatty. 1966. "Pupil Diameter and Load on Memory." *Science* 154, no. 3756: 1583–1585. https://doi.org/10.1126/science.154.3756.1583.

Kinzuka, Y., F. Sato, T. Minami, and S. Nakauchi. 2021. "Effect of Glare Illusion-Induced Perceptual Brightness on Temporal Perception." *Psychophysiology* 58, no. 9: e13851. https://doi.org/10.1111/psyp.13851.

Kloosterman, N. A., T. Meindertsma, A. M. van Loon, V. A. F. Lamme, Y. S. Bonneh, and T. H. Donner. 2015. "Pupil Size Tracks Perceptual Content and Surprise." *European Journal of Neuroscience* 41, no. 8: 1068–1078. https://doi.org/10.1111/ejn.12859.

Kominsky, J. F., and B. J. Scholl. 2020. "Retinotopic Adaptation Reveals Distinct Categories of Causal Perception." *Cognition* 203: 104339. https://doi.org/10.1016/j.cognition.2020.104339.

Kominsky, J. F., B. Strickland, A. E. Wertz, C. Elsner, K. Wynn, and F. C. Keil. 2017. "Categories and Constraints in Causal Perception." *Psychological Science* 28, no. 11: 1649–1662. https://doi.org/10.1177/0956797617719930.

Laeng, B., and T. Endestad. 2012. "Bright Illusions Reduce the Eye's Pupil." *Proceedings of the National Academy of Sciences* 109, no. 6: 2162–2167. https://doi.org/10.1073/pnas.1118298109.

Mascalzoni, E., L. Regolin, G. Vallortigara, and F. Simion. 2013. "The Cradle of Causal Reasoning: Newborns' Preference for Physical Causality." *Developmental Science* 16, no. 3: 327–335. https://doi.org/10.1111/desc.12018.

Michotte, A. 1963. *The Perception of Causality*, edited by T. R. Miles and E. Miles. Basic Books (Original work published 1946). Basic Books.

Pelli, D. G. 1997. "The VideoToolbox Software for Visual Psychophysics: Transforming Numbers Into Movies." *Spatial Vision* 10, no. 4: 437–442. https://doi.org/10.1163/156856897x00366.

Raisig, S., T. Welke, H. Hagendorf, and E. van der Meer. 2010. "I Spy With My Little Eye: Detection of Temporal Violations in Event Sequences and the Pupillary Response." *International Journal of Psychophysiology* 76, no. 1: 1–8. https://doi.org/10.1016/j.ijpsycho.2010.01.006.

Rolfs, M., M. Dambacher, and P. Cavanagh. 2013. "Visual Adaptation of the Perception of Causality." *Current Biology* 23, no. 3: 250–254. https://doi.org/10.1016/j.cub.2012.12.017.

Sato, F., B. Laeng, S. Nakauchi, and T. Minami. 2020. "Cueing the Necker Cube: Pupil Dilation Reflects the Viewing-From-Above Constraint in Bistable Perception." *Journal of Vision* 20, no. 4: 1–14. https://doi.org/10.1167/jov.20.4.7.

Saxe, R., and S. Carey. 2006. "The Perception of Causality in Infancy." *Acta Psychologica* 123, no. 1–2: 144–165. https://doi.org/10.1016/j.actpsy.2006.05.005.

Schlottmann, A., and N. H. Anderson. 1993. "An Information Integration Approach to Phenomenal Causality." *Memory & Cognition* 21, no. 6: 785–801. https://doi.org/10.3758/BF03202746.

Schlottmann, A., E. D. Ray, A. Mitchell, and N. Demetriou. 2006. "Perceived Physical and Social Causality in Animated Motions: Spontaneous Reports and Ratings." *Acta Psychologica* 123, no. 1: 112–143. https://doi.org/10.1016/j.actpsy.2006.05.006.

Scholl, B. J., and K. Nakayama. 2004. "Illusory Causal Crescents: Misperceived Spatial Relations due to Perceived Causality." *Perception* 33, no. 4: 455–469. https://doi.org/10.1068/p5172.

Scholl, B. J., and P. D. Tremoulet. 2000. "Perceptual Causality and Animacy." *Trends in Cognitive Sciences* 4, no. 8: 299–309. https://doi.org/10.1016/S1364-6613(00)01506-0.

Straube, B., and A. Chatterjee. 2010. "Space and Time in Perceptual Causality." *Frontiers in Human Neuroscience* 4: 28. https://doi.org/10.3389/fnhum.2010.00028.

Urai, A. E., A. Braun, and T. H. Donner. 2017. "Pupil-Linked Arousal Is Driven by Decision Uncertainty and Alters Serial Choice Bias." *Nature Communications* 8, no. 1: 14637. https://doi.org/10.1038/ncomms14637.

Völter, C. J., and L. Huber. 2021. "Dogs' Looking Times and Pupil Dilation Response Reveal Expectations About Contact Causality."

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Biology Letters 17, no. 12: 20210465. https://doi.org/10.1098/rsbl.2021.0465.

Yoshimoto, S., and T. Hayasaka. 2022. "Common and Independent Processing of Visual Motion Perception and Oculomotor Response." *Journal of Vision* 22, no. 4: 1–20. https://doi.org/10.1167/jov.22.4.6.

Young, M. E. 1995. "On the Origin of Personal Causal Theories." *Psychonomic Bulletin & Review* 2, no. 1: 83–104. https://doi.org/10.3758/BF03214413.

Young, M. E., and O. Falmier. 2008. "Launching at a Distance: The Effect of Spatial Markers." *Quarterly Journal of Experimental Psychology* 61, no. 9: 1356–1370. https://doi.org/10.1080/17470210701595522.

Young, M. E., E. T. Rogers, and J. S. Beckmann. 2005. "Causal Impressions: Predicting When, Not Just Whether." *Memory & Cognition* 33, no. 2: 320–331. https://doi.org/10.3758/BF03195320.

Zhang, F., S. Jaffe-Dax, R. C. Wilson, and L. L. Emberson. 2019. "Prediction in Infants and Adults: A Pupillometry Study." *Developmental Science* 22, no. 4: e12780. https://doi.org/10.1111/desc.12780.

14698986, 2025, 6, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/psyp.70080 by <Shibboleth>-member@ucas.ac.cn, Wiley Online Library on [05/06/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License