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Causality modulates perception of apparent motion stimuli

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ABSTRACT

Previous studies have shown that contextual information can alter judgments of apparent motion. Specifically, the presence of causal information can even override the shortest-path bias, if the shortest path is inconsistent with a causal interpretation of the motion event. While these results demonstrate that judgments of apparent motion are affected by causality, how causality modulates lower-level spatiotemporal processing is not yet understood. Moreover, it is unclear whether subjects' judgments of apparent motion are the result of perceptual processing or higher-level reasoning. Addressing these questions, we investigated whether causal information could influence detection sensitivity in an apparent motion display. Our apparent motion displays involved two vertically stacked semicircular tubes, and contextual information suggested either motion through the top or bottom tube. Each tube contained a small aperture that would flash, appearing as if the launched object was briefly visible along the motion-path. In addition, contextual information could also be inconsistent with the flash location. In our first experiment, participants judged the location of the target flash under causal and noncausal conditions. In experiment 2, we compared the effect of causality with motion priming, a noncausal cue that may covary with the causal cue. In both experiments, detection was most influenced by causal information, being most accurate when causality was consistent with the target flash and least accurate when causal information acted as a distractor– suggesting that the visual system generates spatiotemporal predictions of object motion during perceived causal interactions.

1. Introduction

In apparent motion, the alternating presentation of two sensory objects gives rise to the experience of a single object smoothly translating to a new position. The path taken by the unified object is not displayed, and it is left to the visual system to fill in. However, when asked, participants can easily define the trajectory the object is moving along, even though there is no external support to pick any one trajectory over another (Wertheimer, 2018). In the simplest cases of apparent motion, the system represents a path that is the shortest between the two flashed positions. This is consistent with the principle for least action, which is used to derive all classical equations of motion. An object in motion will move through space along a path that requires the least action – this is a straight path if there is nothing between the two points in space. However, if the configuration space is more complicated and involves constraints on object motion, like a curved tube between two points, then the object's motion will be constrained by the submanifold of allowable positions (Shepard & Zare, 1983). These findings suggest that the shortest-path bias can be overcome to yield a perception of a longer, curved path, if the perceived scene suggests that a curved path will require less action than a straight path.

In a similar line of research, Kim, Feldman, and Singh (2013) leveraged the fact that human cognition can exploit the law-like patterns of natural scenes (Battaglia, Hamrick, & Tenenbaum, 2013; Deeb, Cesanek, & Domini, 2021; Freyd, Pantzer, & Cheng, 1988; Freyd, 1983; McIntyre, Zago, Berthoz, & Lacquaniti, 2001) and found that the visual system may utilize causal information to disambiguate apparent motion events. Participants observed a sequence of chronologically progressing static images that resulted in an apparent collision. A curved opaque tube was presented, and participants indicated whether the motion target appeared to be moving horizontally or along the curved tube (through the presented semicircular tube). When contextual information suggested that the launch was horizontal, participants showed a preference for the straight path. When the collision suggested that the launched object moved along the curved path, participants' judgements were consistent with kinematics – overriding the preference to perceive

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the shortest motion path in apparent motion sequences. However, the process of asking a participant to pick a motion path after the fact is susceptible to cognitive bias and it is possible that the utilization of causal cues to disambiguate an apparent motion event occurs in cognition, rather than in perception.

In this article we aim to study perceptual sensitivity along the motion path suggested by causality. While there is a long-standing debate as to whether causality is a cognitive or perceptual phenomenon (Michotte, 1963; Scholl & Tremoulet, 2000), there is strong evidence that kinematic constraints and causality are available cues to the visual system. First, the results of Rolfs, Dambacher, and Cavanagh (2013) point toward a visual adaption process specific to causal launches. In fact, they found retinal specificity of aftereffects that strongly suggests that the attribution of causality to a motion event occurs in perception, rather than in cognition. Furthermore, studies in predictive eye movements have demonstrated that contextual factors from the visual scene can serve as cues that influence the anticipatory eye movement in smooth pursuit. Specifically, Badler, Lefevre, and Missal (2010) found that when participants viewed an object colliding with a second object, their anticipatory pursuit eye movements were faster and more accurate if the second object moved in a manner consistent with kinematics and causal expectation (see also Kowler et al., 1984, 1995). These results suggest not only that causality is perceivable, but also that causality and kinematic constraints aid in visual predictions.

Subjective tasks involving causal phenomenology are not capable of probing the visual system's ability to leverage causal information, either to predictively complete the apparent motion path or to shift attention. Thus, to study the effect causality has on visual ability to perceive stimuli along a motion path, we investigated whether causal contextual cues increased detection accuracy along the motion path prescribed by kinematics and causality. If the visual system can use causal information to fill in the motion of an apparent motion sequence, we should predict enhanced processing of stimuli along the motion path suggested by the causal cues, and a decrease in accuracy for the non-cued motion path. Our participants were shown apparent motion stimuli with causal contextual cues that suggested movement through one of two curved motion paths. In each trial, a small aperture along one of the motion paths would flash. The appearance of the flash could be consistent with the kinematics of the event, thus appearing along the motion path reinforced by the collision event (Anstis & Ramachandran, 1987); or inconsistent, appearing on the motion path not suggested by the contextual cues. If the visual system can make predictions by integrating causal information with apparent motion, task accuracy should increase when the flash placement is consistent with the causal launch and should decrease when the flash is inconsistent with causal cues.

2. Experiment 1

In Experiment 1, we hypothesize that causal collision events that follow kinematic geometry will elicit greater detection accuracy than apparent motion stimuli devoid of causality or proper kinematic constraints. More specifically, we predict that signal detection in the causal conditions would be dependent on whether the to-be-detected illuminated aperture was consistent with the causal context. In other words, we predicted an interaction effect. On each trial, participants viewed either a causal (Fig. 1a) or non-causal "reversed" (Fig. 1b) apparent motion sequence. In the causal condition a context object appeared to collide with a target object that moved through a semi-circular tube and collided with an object on the other end of the tube. The non-causal condition was the same sequence of events as above but in reverse order, thus dissociating the motions of each of the apparent motion objects. As shown in Fig. 1, the semi-circular tubes contained a small aperture that would flash, appearing as if the launched object was briefly visible along the motion-path and participants were tasked with judging whether the top or bottom aperture had flashed. Moreover, we imposed a separate fixation task, to ensure that our target effect can be reasonably attributed to perception or an involuntary attention shift to the target motion path, which further strengthens the possibility of a low-level effect of causality. If the visual system does not leverage causal information as a predictive cue and instead causality is post-perceptual judgement, then we should not expect any difference in performance between causally consistent and inconsistent trials.

2.1. Experiment 1 method

2.1.1. Participants

Twenty-seven participants were recruited for Experiment 1 from the UCLA undergraduate participant pool for course credit. Informed consent was obtained, and all participants were treated in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki). All research activities were approved by the UCLA institutional review board.

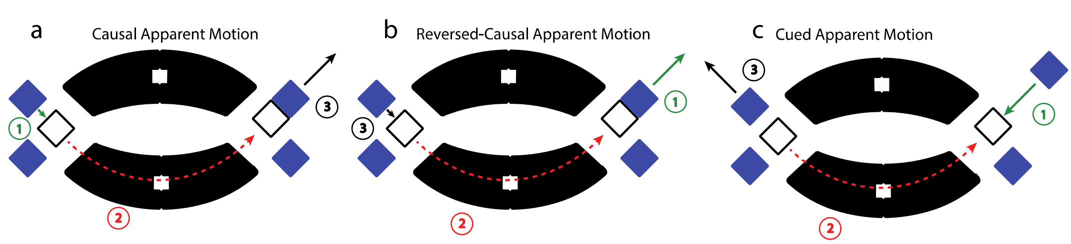

Fig. 1. Apparent motion displays and task design. (a) Example of a *Causal and Consistent* apparent-motion display used in Experiments 1 & 2. (1) A square context object (blue) on the left-side of the display is relocated from its original position to be in contact with the moving object (white). (2) After contact the moving object disappears, and a flash occurs in the bottom tube. The moving object reappears on the opposite side, suggesting movement along the causally consistent motion-path (red arrow). (3) The moving object collides with the context object on the opposite side of the display, and in the following frame that context object appears further away, thus creating a percept of a second launching (black arrow). A *Causal and Inconsistent* trial would appear identically expect that the flash would occur in the aperture that is not along the causal motion-path. (b) Example of a Reversed display used in Experiment 1. The apparent motion sequence is a reversal of those found in the Causal apparent-motion displays. (1) The context object on the opposite side of the white moving object moves away from the center of the screen. (2) The white context object moves, without any contact, from the left side of the screen to the right, appearing in the aperture as it "passes through" the tube. (3) Lastly, the context object that initially appeared on the same side of the moving object, moved toward the tube. (c) Example of a non-causal *Cued and Consistent* display used in Experiment 2. (1) The first motion in the display (green) is the motion of a context object on the opposite side of the moving object moving toward the cued tube. (2) Like all other conditions, the moving object disappears, and the aperture along the cued motion-path (red arrow) is illuminated. The moving object then reappears on the side opposite to its initial position. (3) Finally, the context object that has not yet moved jumps away from the cued tube. This apparent motion stimulus can be interpreted as the moving object traveling along the same semicircular tube cued by the context object movement. So, it is cued (by the context object on the right) and consistent (with the moving object's tube). While, as in (b), (c) shows no causal contact between objects, c.1 aimed to bring participants attention to a particular aperture, while b.1, does not. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.1.2. Apparatus

Experiment 1 was custom scripted using the Python library PsychoPy (Peirce et al., 2019) and presented on a 21″ ViewSonic CRT monitor with a refresh rate of 85 Hz and a resolution of 1280 × 1024. A viewing distance of 91 cm (3 feet) was used, and each pixel subtended about 0.02 degrees of visual angle.

2.1.3. Experimental stimulus and task

On every trial, several high-contrast objects were presented against a gray background: Four blue square "context objects" of side length 17 pixels (0.33°), one white square "moving" object of side length 17 pixels (0.33°), a fixation point in the middle of the display, and two elliptical black half-annuli oriented horizontally that represent upper and lower tubes in between the two sets of context objects (Fig. 1). The total width of each tube subtended about 4.15°, and the distance between the highest point on the top tube and the central fixation point, or the lowest point on the bottom tube and the central fixation point, subtended about 1.29°.

Two small square apertures with side length 8 pixels (0.15°) were placed on the black tubes, colored the same gray as the background and located centrally on the highest crest and lowest valley of the upper and lower tubes, respectively. See Fig. 1 for an example illustration of the apparent motion display.

During a trial, a series of apparent-motion images would be presented. First, the initial image showing all parts of the stimulus was displayed for 25 frames (0.3 s). This image was identical for all four conditions. On every trial, the context objects exhibited one of four specific randomly selected patterns of movement:

1. *Causal and Consistent*: The context object on the same side of the semicircular tubes as the moving object is shown to push the moving object into either the top or the bottom tube, by jumping 12 pixels (0.23°) toward the moving object, and this was displayed for 2 frames (0.02 s). In the third image, displayed for 2 frames (0.02 s), the moving object disappeared. Then in the fourth image, displayed for 3 frames (0.035 s), the aperture located along the motion path suggested by the movement of the context object flashes. For example, if the upper left context object pushes the moving object down into the lower tube (as in Fig. 1a), then the lower aperture will illuminate. In the fifth image, displayed for 2 frames (0.02 s), the aperture again turned gray. In the sixth image, displayed for 2 frames (0.02 s), the moving object appeared on the side of the tubes opposite to its original position touching the context object in the mirror symmetrical position as the originally moving context object in the second image. Lastly, in the final image, displayed for 25 frames (0.3 s), the context object that is in contact with the moving object jumped 12 pixels (0.23°) away from the moving object. The overall percept was that of a collision, which forced the white square through the tube and into another collision on the opposite side.
2. *Causal and Inconsistent*: The trial sequence is identical to *Causal and Consistent*, except that the illuminated aperture is located along the motion path not suggested by the movements of the context objects. Following the example used previously, if the lower semicircular tube is suggested, then the upper aperture will illuminate.
3. *Reversed Consistent*: The trial sequence is identical to *Causal and Consistent* sequence, except that the order of the context object movement is reversed (see Fig. 1b). The context object opposite to the moving object's initial position moves first, then the moving object moves, and finally the context object on the same side as the moving object's initial position moves. This reversal of context object movement destroys the causal relationship between the context and moving objects. It is therefore not meaningfully consistent nor inconsistent with the appearance of the flash. However, reversed stimuli are tested to determine whether the motions themselves can successfully cue one aperture over the other.
4. *Reversed Inconsistent*: The order of the context object movement is again reversed; however, the displayed sequence is the reversal of a *Causal and Inconsistent* display.

Participants were asked to fixate the center point and indicate whether the flash had occurred within the top or the bottom aperture. The central fixation task occurred concurrently with the flash detection task: the fixation point was replaced by an "X" or a "V" while the aperture was illuminated, and participants were required to indicate the presented letter. There was a total of 304 trials, 76 trials from each of the four conditions, all randomly interleaved. The direction of the moving object was leftward for half of the trials and rightward for the remaining half, randomly selected on each trial. To avoid teaching the participant to ignore the movement of the context objects, no corrective feedback was given.

2.1.4. Luminance thresholding

To avoid ceiling or flooring effects, a preliminary luminance thresholding task was used to set the luminance intensity of the signal aperture in the main experiment. Performance accuracy of 71% in the absence of any context object movement was targeted. The luminance thresholding task was identical to the main experimental task, except that the blue context objects were stationary throughout each trial. The luminance intensity of the target aperture was determined using a 2-down 1-up staircase procedure (Levitt, 1971) with an initial supra-threshold intensity value of 124 and a step size of 2, with a bottom staircase value equal to the background (100).[1] Forty-eight trials were collected, and the threshold was estimated by averaging the last six reversals along with the final staircase value.[2]

2.2. Experiment 1 results

All trials in which the fixation task was incorrectly answered were discarded. An average of 16 out of 304 total trials were discarded for each participant (*SD* = 14). No more than 33 out of 304 trials (11%) were discarded for all but two participants. Fifty-seven (19%) and 50 (16%) trials were discarded in these two participant datasets, respectively.

As shown in Fig. 2, consistent with our hypothesis, participant judgments were most accurate in the *Causal and Consistent* condition, and least accurate when the stimuli exhibited causality, but the target flash was not consistent with the context object motion (*Causal and Inconsistent)*. We statistically examined this interaction effect with a two-way analysis of variance (ANOVA) with the factors sequence order (Causal vs Reversed) and consistency (Consistent vs Inconsistent). Critically, the interaction effect was highly significant, $F(1,23) = 14.07$, $p = 0.001$, $\eta^2 = 0.17$. Follow-up pairwise comparisons found a significant difference between the *Causal and Consistent* and *Causal and Inconsistent* conditions, $t(23) = 2.77$, $p = 0.01$, $d = 0.57$; and between the *Reversed Consistent* and *Reversed Inconsistent* conditions, but in the opposite direction, $t(23) = -2.33$, $p = 0.03$, $d = -0.48$. To confirm that there was no location bias, the effect of flash location was included in a follow up 3-way analysis of variance (ANOVA) along with the factors sequence order (Causal vs Reversed) and consistency (Consistent vs

[1] Although the monitor was calibrated, we chose to simply work with the pixel values since the goal was to find a pixel value for the flash detectable about 71% of the time.

[2] Prior to any statistical analysis, an inspection of the luminance thresholding data was first carried out to ensure participants were indeed at visual threshold during the main experiment. In experiment 1, three out of 27 participants exhibited monotonically rising staircase values arising from either exclusively pressing a single response key or from repeated and regular alternation between keys. Because these participants exhibited clear evidence of poor task compliance, their data were discarded prior to the main reported analysis.

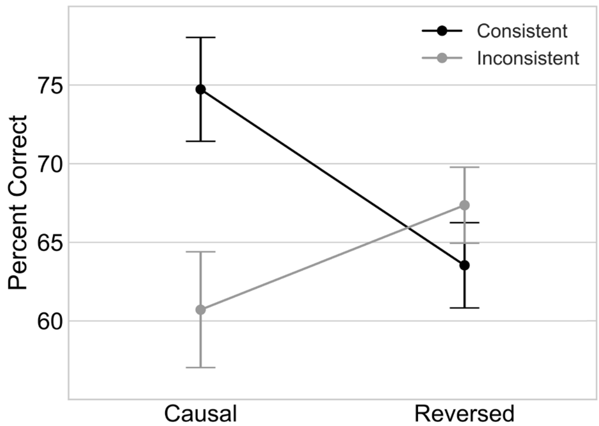

Fig. 2. Experiment 1 results. The effect of causality with consistent (black) and inconsistent (gray) stimuli. Here and in future plots, the error bars are ±1 SEM.

Inconsistent). The main effect of flash location was not significant, $F(1,23) = 1.78$, $p = 0.195$, nor were any of the interactions with flash location. However, the key interaction effect between causality and consistency remained in this exploratory analysis, $F(1,23) = 14.25$, $p = 0.001$.

2.3. Experiment 1 discussion

Experiment 1 examined the effect of an apparent motion causal stimulus on the detection of an illuminated aperture. We predicted that accuracy would be modulated more strongly by causal trials than by reversed trials. That is, we predicted that *Causal and Consistent* trials would result in greater accuracy, while *Causal and Inconsistent* trials would result in poorer accuracy, relative to the equivalent reversed conditions. In Experiment 1, we found that the causal conditions did in fact strongly modulate performance. Regardless of consistency, the reversed conditions elicited performance in between the extremes elicited by the causal stimuli. There was a significant difference in performance between the two reversed conditions, which suggests that the reversed sequences may weakly cue the visual system, but in the opposite direction. As shown in Fig. 1b, the first part of the reversed sequence involves a context object on the opposite side moving away from the center of the screen. If, for instance, in the *Causal and Consistent* condition, the collision suggested a movement through the bottom tube, then the first context object moved diagonally downward and the second context objective moved diagonally upward. Therefore, in the corresponding reversed condition, the first context object moved diagonally upward, possibly directing attention away from the flash aperture. This may explain why inconsistent trials were slightly more accurate than consistent trials in the reversed conditions. Regardless, Fig. 2 suggests that without causal contextual information, neither aperture was strongly cued.

Experiment 1 demonstrated that an apparent motion stimulus exhibiting a causal relationship between moving objects influences detection during an objective perceptual task more than an apparent motion stimulus exhibiting no coherent causal relationship. This result suggests that mechanical causality may directly influence perception, resulting in downstream effects on visual performance. However, an alternative explanation for these findings may be that some noncausal cues suggestive of a particular motion path covary with the causal cue, potentially involving attentional priming or some other noncausal effect. Specifically, in a causal condition, the fact that the first context object's motion direction pointed to, and therefore cued, the consistent aperture location might in itself explain the interaction effect obtained. Experiment 2 addresses this concern by introducing a different noncausal apparent motion sequence designed to maintain as much noncausal perceptual cueing to the consistent aperture as possible.

3. Experiment 2

In Experiment 2, the previous noncausal stimuli were replaced with new stimuli designed to cue the consistent aperture as strongly as possible without coherent causal information. The experimental design was otherwise identical to Experiment 1. We hypothesized that if causality imparts a specific and unique influence onto the perception of an apparent motion stimulus, then the cue toward the consistent aperture from a causal stimulus should modulate detection more strongly than the cue imparted by a noncausal stimulus.

3.1. Experiment 2 method

3.1.1. Participants

Nine UCLA students serving as research assistants who were naïve to the purposes of the study were recruited for Experiment 2, similarly as in Experiment 1.

3.1.2. Apparatus

Due to limitations presented by the Covid-19 pandemic, the study was carried out remotely on participants' personal laptop computers. As a result, while the refresh rate was fixed to 60 Hz for all participants, it was not feasible to control other computer specifications. All participants were instructed to sit comfortably and maintain the same position throughout the entire experiment and maintain a viewing distance of 60.5 cm (2 feet). The monitor resolutions ranged from 1280 × 800 to 2560 × 1600, with four participants using a resolution of 1440 × 900. Similarly, each participant's monitor size varied, ranging from 28.7 cm to 38.2 cm. Subsequently, the differing monitors resulted in each pixel subtending varying degrees of visual angle, ranging from approximately 0.01° to 0.02°. The median and mean visual angle per pixel value was approximately 0.02°, as in our previous experiment. Because this study involves fast apparent-motion stimuli located exclusively near central fixation and relies on causal and geometric contingencies between moving objects, we do not anticipate that these variations will materially alter the conclusions of this study. Furthermore, our thresholding procedure and within-subject design mitigate concerns about varying experimental apparatuses.

3.1.3. Experimental stimulus and task

Unlike Experiment 1, the signal aperture was illuminated for a single frame (0.017 s). All other stimulus properties were unchanged. Experiment 2 contained the previous *Causal and Consistent* and *Causal and Inconsistent* conditions, however, the previous noncausal conditions were replaced by the following noncausal cued conditions, illustrated in Fig. 1*c*:

1. *Cued and Consistent*: The context object on the opposite side of the moving object jumps toward the cued semicircular tube. The moving object then disappears, and the cued aperture is illuminated. The moving object then reappears on the side opposite to its initial position. Finally, the context object that has not yet moved jumps away from the cued tube. This apparent motion stimulus can be interpreted as the moving object traveling along the same motion path cued by the context object movement, but in the incorrect direction. Therefore, both context objects act as noncausal cues to shift attention toward the illuminated aperture, both before and after the target flash.
2. *Cued and Inconsistent*: The trial sequence is identical to *Cued and Consistent*, except that the illuminated aperture is located along the motion path not suggested by the movements of the context objects.

3.2. Experiment 2 results

All trials in which the fixation task was incorrectly answered were discarded from the analysis. An average of 14 out of 304 total trials were discarded for each participant ($SD = 10$). No more than 32 out of 304 trials (10.5%) were discarded for any single participant.

Data from all eligible trials were submitted to a 2 (causality: Causal vs Cued) × 2 (consistency: Consistent vs Inconsistent) repeated measures ANOVA to determine whether an interaction effect again exists between consistency and causality. The interaction effect was indeed significant, $F(1,8) = 8.62$, $p = 0.019$, $\eta^2 = 0.05$. Follow-up pairwise comparisons revealed that *Causal and Consistent* and *Causal and Inconsistent* were significantly different, $t(8) = 2.88$, $p = 0.02$, $d = 0.96$. In contrast, *Cued and Consistent* and *Cued and Inconsistent* were not significantly different $t(8) = 1.84$, $p = 0.10$, $d = 0.62$. This indicates that attentional cueing without causality played an insignificant role. The main conclusion here is that causality (but not cueing) was indeed primarily responsible for the effect found in Experiment 1.

As before, to confirm that there was no location bias, the effect of flash location was included in a follow up 3-way analysis of variance (ANOVA) along with the factors causality (Causal vs Cued) and consistency (Consistent vs Inconsistent). The effect of flash location was not significant, $F(1,8) = 2.43$, $p = 0.16$ and the interaction effect still exists between consistency and causality, $F(1,8) = 8.73$, $p = 0.018$.

3.3. Experiment 2 discussion

Experiment 2 compared the influence of causality with the influence of non-causal cueing during a flash detection task. We again found that the causal condition modulated accuracy and that this effect was statistically significant. We also found a numerical difference in the cued condition between consistent and inconsistent trials, as illustrated in Fig. 3. However, this effect did not reach statistical significance with our sample size. These results suggest that a causal relationship does uniquely influence participant behavior without depending on other coexisting non-causal cues. Both causal and cued conditions elicit apparent motion percepts but differ with respect to causality. It is possible that causality exerts a particular influence on the percept of apparent motion, making the experience of motion more salient.

If our Experiment 1 results were exclusively due to the first context object acting as an exogenous motion cue to shift attention, then we should expect no difference in response patterns between the causal and cued conditions, as both *Causal and Consistent* and *Cued and Consistent* conditions contain a context object moving toward the target aperture prior to the flash. If instead the effect is due to the visual system predictively filling-in the motion path, we should see an effect in the causal condition only.

It is noteworthy that the results of the current study elicited a markedly stronger causal effect than in Experiment 1, and that the exhibited variability was similarly increased. While it is not possible to pinpoint the cause of the effect size difference, we do note that in Experiment 2 the participants were laboratory research assistants who were more experienced with psychophysical experiments and more motivated. The overall performance in Experiments 1 & 2 were the same (67% correct), indicating that the thresholding procedure prior to the main experiments was reasonably effective. It is unclear whether the difference in flash duration or viewing distance between the two experiments could explain the effect size difference. Though we are uncertain as to the exact cause of the effect size difference, we believe that this difference is non-central to our hypothesis.

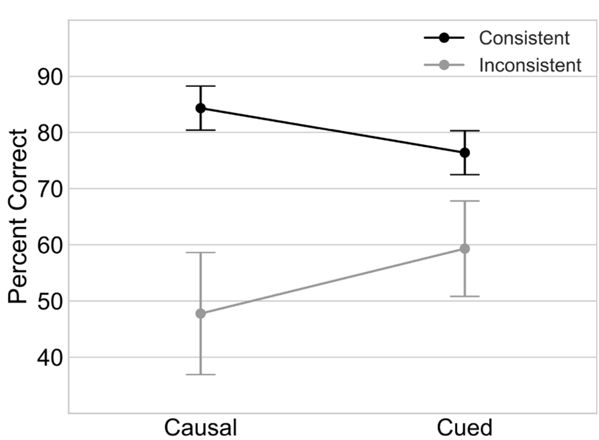

Fig. 3. Experiment 2 results. The effect of causality with consistent (black) and inconsistent (gray) stimuli.

4. General discussion and conclusions

We proposed that causal information could be leveraged to increase detection along an apparent motion path. More specifically, we predicted that detection accuracy would be greater when causality was present and the target flash was consistent with the causal information, but poorer when causality was present, and the target flash was inconsistent with the causal information. The results of Experiment 1 and Experiment 2 reflect these predictions and suggest that causality and kinematic regularities promote an increase in visual performance along the causal motion path.

We argue that the presence of causality in the consistent condition acted as a predictive cue, which aided the visual system in processing the ambiguous apparent motion stimulus. Previous results have shown that as task difficulty increases, so too does reliance on predictive representations of motion (Deeb et al., 2021). It is likely that the implementation of the fixation task on letter discrimination, which occurred concurrently with the flash detection task, acted as a distractor to the target flash and thus increased task difficulty.

This study employed performance accuracy as the outcome measure. While using signal detection measure *d'* may have provided stronger evidence for a perceptual or attentional process rather than a cognitive process potentially involving bias, the *d'* calculation assumes a two-condition design (signal and noise). Because the goal of the current study was to investigate an interaction effect, we adopted a four-condition, randomly interleaved design in Experiments 1 & 2. This design provided the clearest framework to explore any possible interaction effect, however necessitating the use of detection accuracy. Nevertheless, we are confident that our results reflect visual sensitivity with little contamination from position bias. In our current design, position bias, i.e., favoring one aperture over the other, cannot explain the observed interaction effects because all four conditions were evenly distributed between the “upper” and “lower” paths. Furthermore, we found no effect of flash location (upper or lower) on participants' behavior in both studies.

Collectively, these results point toward an internal mechanism that generates spatial predictions of object motion during perceived causal interactions. It is possible that this increase in performance is due to visual attention being shifted to the anticipated location or that causality increases the perception of apparent motion, or that our results are due to both attentional and perceptual mechanisms. If the visual system can use causal information to fill in the path of an apparent motion sequence, we should predict an increase in sensitivity to stimuli along the motion path suggested by the causal cues, relative to objects on the non-cued motion path. Similarly, the causal context could act as an exogenous motion cue to shift attention, enhancing visual processing along the cued apparent motion path. While these two accounts predict similar outcomes, they diverge in how they explain changes in detection accuracy. The perceptual account argues that the visual system predictively fills in the apparent motion path, on the basis of causal information– thus increasing sensitivity by increasing the signal-to-noise ratio. Whereas an attentional account of causally cued apparent motion argues that the causal contexts can shift the location of visuospatial attention, allowing for enhanced processing of attended information and decreased processing of unattended information (Posner, 1994). Given that visuospatial attention is related to eye movements (Hoffman &

Subramaniam, 1995), it follows from the results of Badler et al. (2010) that the locus of visual attention should coincide with the anticipated trajectory of the launched object. Such line of reasoning predicts that if a visual event (such as a stimulus flash) coincides in location and time with the anticipatory attention along the path of apparent motion caused by mechanical collision, detection performance of such an event will be increased as attention is focused on the correct location. However, as participants were required to perform a central fixation task, our results are likely not due to overt shifts in orienting (i.e., eye-movements, similar to Badler et al. (2010)), but may be the result of covert shifts in visuospatial orientation (Posner, 1980).

Our results either suggest that the difference in accuracy witnessed in the causal condition (in both Experiment 1 & 2) is either not strictly due to a shift in attention, or that the perception of causality has a stronger influence on visuospatial attention, beyond an exogenous motion cue. The effect of causality on detection, relative to the cued condition, could be a result of both attentional and perceptual mechanisms. That is to say, the context object movement cues attention to a particular aperture while also increasing the percept of apparent motion.

Moreover, our findings demonstrate that perceptual interpolation follows kinematic principles (Carlton & Shepard, 1990; Kim et al., 2013; McBeath & Shepard, 1989; Shepard, 1984, 1994) and that detection accuracy increases along the “filled-in” path of motion. These results help establish causality as a perceptual process and provide more fine-grained detail about the interpolative computations that underlie apparent motion.

Author contributions

A.-R. Deeb developed the study concept in collaboration with A. Silva and Z. Liu. All authors contributed to the study design. Data collection was performed by all authors and in the laboratory of Z. Liu at UCLA. Data were analyzed and interpreted by A.-R. Deeb & A. Silva under the supervision of Z. Liu. A.-R. Deeb and A. Silva drafted the manuscript, and Z. Liu provided critical revisions. All authors approved the final version of the manuscript for submission.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.visres.2022.108120.

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