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Perceiving causal relations between moving objects: Postdictive causal attribution can bias apparent motion correspondence

Sung-Ho Kim† Ye-Eun Jung

Department of Psychology, Ewha Womans University

Comprehension of physical events in terms of cause and effect is fundamental for making sense of and dealing successfully with changes in the dynamic physical world. Previous research has demonstrated that the causal structure of the world can, in some cases, be directly perceived: When two billiard balls collide, observers perceive that the action of one ball caused the other's motion, merging two motion events into a unitary percept. The current study explored whether such casual interpretations can contribute to resolving low-level ambiguities in motion perception. We used a bistable apparent motion display, a motion quartet, which can lead to the perception of either horizontal or vertical motion, and tested the effects of "context objects" which moved in such a way that motion targets appeared to collide with them in either horizontal or vertical dimension. Our results show that contextual motion implying a Michotte-style launch can strongly bias observed motion correspondence, consistent with physical regularities of mechanical causality in a postdictive way. It suggests that the perception of causality is an earlier and more pervasive phenomenon than previously understood, and in fact can influence the perception of motion itself.

Key words : causal perception, apparent motion, motion correspondence, postdiction

† 교신저자 : 김성호, 이화여자대학교 심리학과, (120-750) 서울시 서대문구 이화여대길 52
E-mail: sunghokim@ewha.ac.kr

Understanding dynamic visual events goes far beyond perceiving the coherent and persistent physical structure of moving objects. Just as perceiving static scenes as being made up of the units of objects, people perceptually organize the streams of moving objects into meaningful spatiotemporal units of events (Zacks & Tversky, 2001). One particularly important component of event perception is the causal structure: how a moving object appears to affect another when they come into physical interactions like a collision. Indeed, our visual experiences is not just based on kinematic information extracted from the moving objects, but we sometimes perceive causality directly, which is seemingly a higher-level, unobservable property of motion events.

Perhaps the best known demonstration of causal perception is the "launching effect" (Michotte, 1946/1963): When a moving object suddenly stops adjacent to a stationary object, which then starts to move in the same direction, people tend to see the second object motion as caused by the impact of the first one. Michotte's seminal research and a large body of following studies of causal perception have focused on determining the spatiotemporal factors that mediate such phenomenological experiences of causality in simple mechanical interactions of moving objects (e.g., Boyle, 1960; Choi & Scholl, 2004; Gordon, Day, & Stecher, 1990; Natsoulas, 1961; Schlottmann & Anderson, 1993; Schlottmann & Shanks, 1992; Scholl & Nakayama, 2002, 2004; for a review, see Scholl & Tremoulet, 2000). The convergent findings from this line of research suggest that causal impressions are largely automatic, stimulus driven, and unaffected by higher-level beliefs or intentions. A recent visual adaptation study (Rolfs, Dambacher, & Cavangh, 2013) provided more direct evidence on the low-level perceptual nature of causality. They demonstrated that repeated exposure to causal collisions increased the tendency to perceive subsequent ambiguous events in the same retinal location as non-causal 'passing', i.e., retinotopic aftereffect of causality.

The impression of causality might be a global gestalt imposed upon spatiotemporally contingent motion events in the sense that it merges the two motion events into a unitary percept, giving a continuity of perceived momentum which is transferred from one object to another. A question that has gone largely unnoticed is the influence of such causal structure on other perceptual processes. Just as the interpretation of local features is influenced by the global scene in which they are embedded, the perception of spatiotemporal characteristics of moving objects might be affected by the global causal structure. However, such a possibility has been rarely tested, and only a handful of recent studies have explored the consequences of perceived causality in other visual processes, such as spatial relationship between objects (Buehner & Humphreys, 2010; Scholl & Nakayama, 2004), temporal order of events (Bechlivanidis & Lagnado, 2016), and trajectory of apparent motion (Kim, Feldman, & Singh, 2013).

In this paper, we aimed to study the influence of the perception of causality on the processing of the underlying motion signal itself, using objects undergoing apparent motion. Apparent motion, an illusory continuous motion produced by a rapid succession of static images (Wertheimer, 1912/1961), involves inherent perceptual ambiguities due to its limited sensory information about the motion. First of all, to generate apparent motion, the visual system must match objects at different places across frames as constituting different glimpses of the same moving object, i.e., a correspondence problem. Furthermore, the visual system should determine through which path matched objects are connected to each other. Most related to the current study, Kim et al. (2013) showed that context motion implying causal collision can influence the perceived path of apparent motion in a way consistent with the direction of the launch. In their study, observers viewed apparent motion sequences of two alternately flashing rectangular targets placed at the ends of a semicircular tube (a potential "detour" for the motion path). The trajectory of apparent motion was strongly influenced by the behavior of a pair of additional context objects, such that the target motion could even deviate from the shortest straight path towards a longer, curved one behind (or through) the tube when the contextual motion cued a causal collision in the direction orthogonal to the straight path between the two targets.

The current study tested whether the contribution of perceived causality to resolving ambiguities in apparent motion can extend to the motion correspondence problem. To do so, we employed a biastable apparent motion display, the so-called 'motion quartet' (Ramachandran & Anstis, 1983), in which two pairs of motion targets positioned at diagonally opposite corners of an imaginary rectangle are presented alternately (Figure 1a). The motion correspondence in this situation is physically ambiguous since a target in a frame has two candidate corresponding partners in a next frame, resulting in bistable perception of either horizontal or vertical motion (Figures 1b and 1c). Because the proximity of motion targets is a crucial determinant of motion correspondence (Ullman, 1979), the likelihood of a horizontal (or vertical) motion percept is mainly determined by the horizontal-to-vertical distance ratio (H/V ratio) of the motion quartet: the smaller vertical separation is than the horizontal separation, the more perceptually favored is vertical motion, and

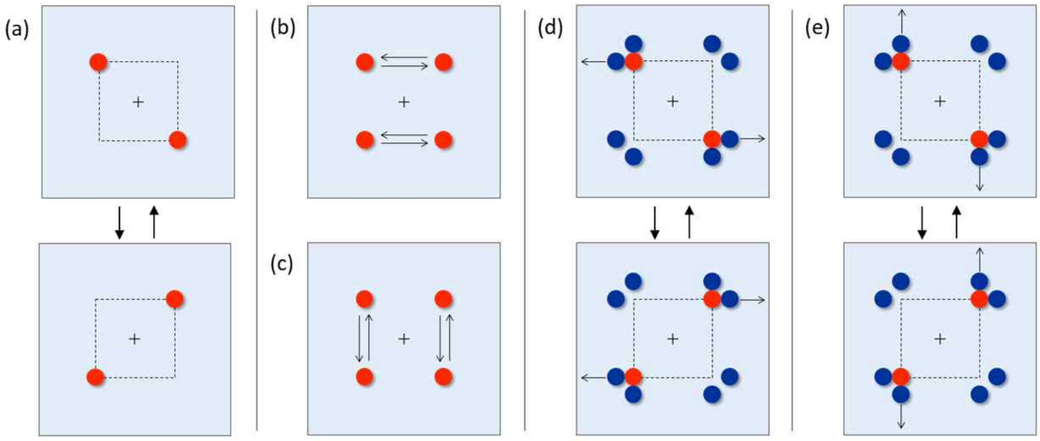

Figure 1. (a) A bistable motion quartet display. Two pairs of motion targets positioned diagonally at opposite corners of an invisible rectangle are presented alternately (the dotted lines indicate the invisible rectangle), leading to a percept of either horizontal (b) or vertical (c) motion. (d and e) Apparent-motion displays used in Experiment 1 of the present study which included four pairs of context objects (blue dots) to the basic motion quartet display. After each target onset, either lateral (d) or top/bottom (e) blue dots immediately adjacent to the targets were displaced laterally or upward/downward and then reverts to their original positions during the interval between the motion targets' disappearance and the appearance of the other motion targets.

vice versa. To investigate the influence of perceived causality in the correspondence- solving process, four additional pairs of "context objects" were included to the quartet, wrapping the four corners of the virtual rectangle. The context objects' displacement was synchronized to the onset of each motion target in a way that the motion targets appeared to collide with and launch them in either a horizontal or vertical dimension: as soon as motion targets appeared, the context objects placed on their left or right sides moved laterally (horizontal-launch display; Figures 1d and 2a), or ones above or below the targets moved upward or downward (vertical-launch display; Figures 1e and 2b). We evaluated the strength of perceived event structure in biasing motion correspondence systematically, by comparing the H/V ratio at which the two motion percepts are equally likely between the horizontal- and the vertical-launch displays. It was expected that context motion implying a Michotte-type launch would decisively bias motion correspondence in accordance with casually coherent interpretations.

Experiment 1

Experiment 1 tested the influence of perceived causality in resolving apparent motion correspondence in motion quartet displays, employing context events implying physical collision either in a horizontal or vertical dimension.

Method

Participants. Six participants (the second author and five naive volunteers) with normal or corrected-to-normal vision completed individual 1-hour sessions. The volunteers signed a consent form that was approved by the University's Institutional Review Board.

Stimuli and design. Participants were seated approximately 60 cm from a 19-inch CRT monitor, and head position was stabilized with a chinrest. The monitor ran at a resolution of 1,024 × 768 pixels with a refresh rate of 120 Hz, and the experiment was controlled by a program written in MATLAB using the Psychtoolbox extensions (Brainard, 1997; Pelli, 1997).

The motion quartet consisted of two pairs of red dots (motion targets; diameter, 16 pixels or 0.52° in visual angle), which were presented alternately at two diagonally opposite corners of an imaginary rectangle on a black background. Each diagonal pair was presented for 150 ms with an interstimulus interval (ISI) of 180 ms. A white fixation cross (0.55° × 0.55°) was always presented at the center of the screen during the entire motion sequence. The H/V ratio (the vertical divided by the horizontal inter-target distance) was varied in seven levels by changing both the vertical and horizontal inter-target distances, such that the sum of the two distances was kept constant at 120 pixels (hence, the perimeter of the imaginary rectangle was fixed at 240 pixels): the larger the H/V ratio was, the smaller the vertical inter-target distance was and the larger the horizontal distance as much. The resultant H/V ratio was either 0.2, 0.4, 0.67, 1.0, 1.5, 2.5 or 5.0, which corresponded to a horizontal inter-target distance of 20, 34, 48, 60, 72, 86, or 100 pixels (0.66°, 1.12°, 1.58°, 1.97°, 2.82° or 3.28°), respectively.

Along with the red target dots, four additional pairs of blue dots (context objects) of the same size appeared immediately on the outer side (left or right) of and above or below the four target dot locations, so that they wrapped the four corners of the virtual rectangular frame. They remained visible across the entire motion sequence while motion targets continued to appear in alternation. According to context object motion, two stimulus displays were constructed. In horizontal-launch displays (Figure 2a), 130 ms after target onset, context objects placed immediately next to each target were

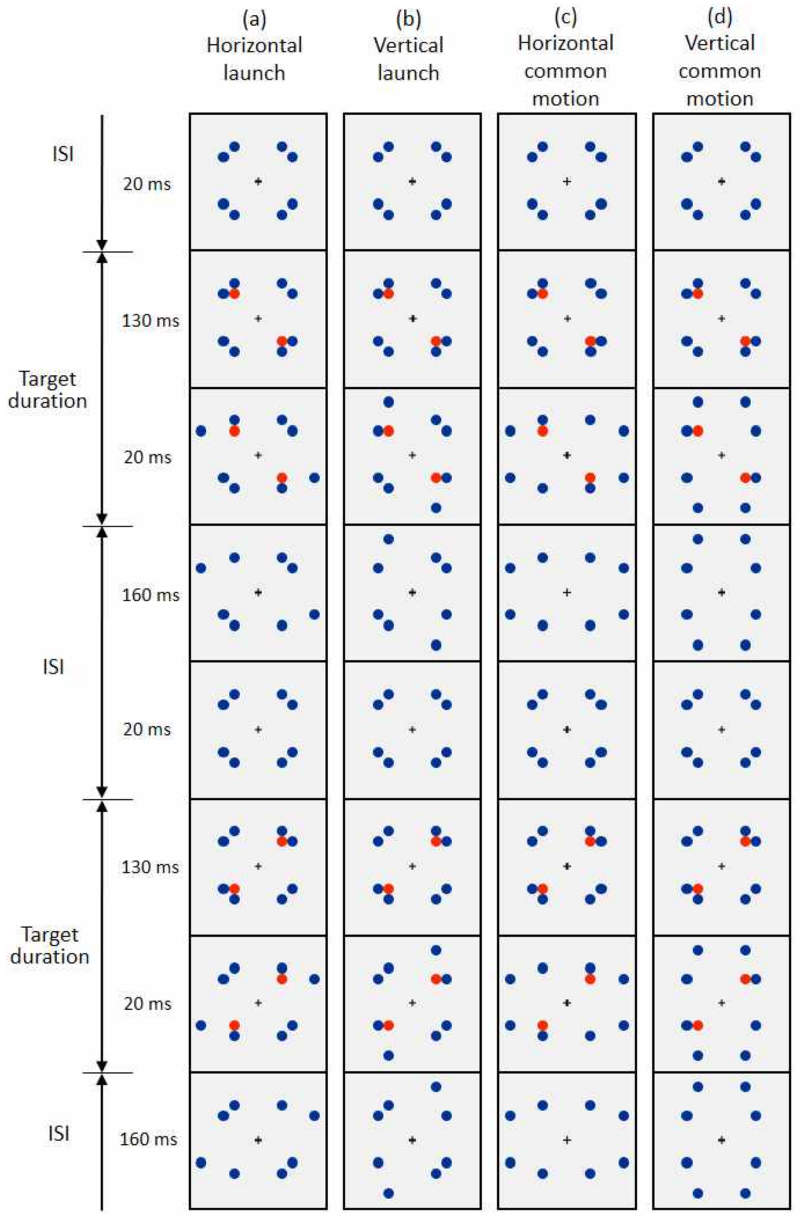

Figure 2. Apparent motion displays and trial sequence used in Experiment 1 (a, b) and Experiment 2 (c, d). In each condition, a trial consisted of three and 5/8 cycles of the eight-frame motion sequence as shown here. In all conditions in both experiments, context objects (blue dots) remained visible across the whole motion sequence, while motion targets (red dots) flashed alternately. The sequence of target dot displacement was identical in all display conditions, but depending on the behaviors of context objects each condition was defined. On half of the trials, the motion sequence started from the frame where motion targets appeared on top-right and bottom-left corners of the imaginary rectangle (the first frame), and on the other half, it started from the frame with targets on the opposite corners (the fifth frame).

displaced outward by 1.8°, and then were returned to their original positions during the ISI (160 ms before the onset of the targets on the opposite corners). The other four context objects located above/below the motion targets remained still in their original positions during the whole motion sequence. In vertical-launch displays (Figure 2b), context objects located immediately above or below the motion targets were displaced upward or downward by 1.8° for the same duration as in horizontal-launch displays, and then returned to their original positions.

Procedure and design. Each trial began with a 500 ms presentation of a central fixation cross, followed by three and 5/8 cycles of an eight-frame motion sequence, then a blank screen. Participants were to indicate whether the red dots appeared to be moving horizontally or vertically by pressing one of two response keys.

Each participant completed a total of 280 experimental trials (2 display types × 7 H/V ratios × 20 repetitions) presented randomly, with three rest breaks after every 70 trials for each. Before the experimental trials participants were ran in 180 practice trials. This lengthy practice session aimed to eliminate the potential influence of perceptual hysteresis, persistence of a percept across consecutive trials despite parameter change to values for which the alternative percept is favored (Hock, Kelso & Schoner, 1993; Shimojo & Nakayama, 1990).

Results and discussion

Figure 3a illustrates the proportion of trials for which observers reported seeing "horizontal" motion. Inspection of this figure suggests two primary tendencies: (1) the smaller H/V ratio was, the more horizontal responses were reported; (2) the horizontal-launch display (M = .61) produced more horizontal motion responses than the vertical-launch display (M = .25) did. These tendencies were confirmed via the following analyses. A 7×2 repeated measures analysis of variance revealed a main effect of H/V ratio, $F(6, 30) = 31.58$, $p < .001$, $\eta_p^2 = .863$ and also a main effect of display type, $F(1,5) = 21.12$, $p = .006$, $\eta_p^2 = .809$. A display type by H/V ratio interaction was also significant, $F(6, 30) = 8.30$, $p = .001$, $\eta_p^2 = .624$, such that the difference between the two displays was smaller at the two largest H/V ratio levels than at other levels. That is, horizontal responses in the horizontal-launch display tended to converge to 0 at the largest H/V ratio, but in the vertical-launch display they did not converge to 1 even at the smallest H/V ratio, possibly due to the combined effect of the vertical launching cue and the vertical motion bias reported in previous studies of the motion quartet stimuli (e.g., Chaudhuri, 1991).

We then calculated the point of subjective equality (PSE), which is the H/V ratio giving rise to 50 % horizontal motion responses, to compare the mean perceived motion of the two displays. Cumulative Gaussian functions were fitted independently to the data for each participant and display type using the psignifit toolbox for Matlab, which implemented the maximum-likelihood method (Wichmann & Hill, 2001a, 2001b). The H/V ratio on the fitted function at which the observer judged the target dots as moving horizontally at 50% probability was taken as the PSE and was used to estimate observers' perceived motion in each display type. As depicted in Figure 3b, the mean PSE for the horizontal-launch display (72.2 pixels, equivalent to 1.51 of H/V ratio, SE = 7.8) was significantly larger than that for the vertical-launch display (31.0 pixels, equivalent to 0.35 of H/V ratio, SE = 5.6), $t(5)$ = 3.49, p = 0.018, d = 1.42.

These results showed that motion correspondence was strongly biased by the direction of context motion, overshadowing the default tendency of pairing "nearest neighbors" (Ullman, 1979). In the vertical launch display, for example, vertical motion was about 3.5 times more likely to be perceived than horizontal motion (77.5% of vertical vs. 22.5% of horizontal responses) even at 0.67 of H/V ratio, which could be more favorable to horizontal motion without the context object motion. It suggests that observers attributed the

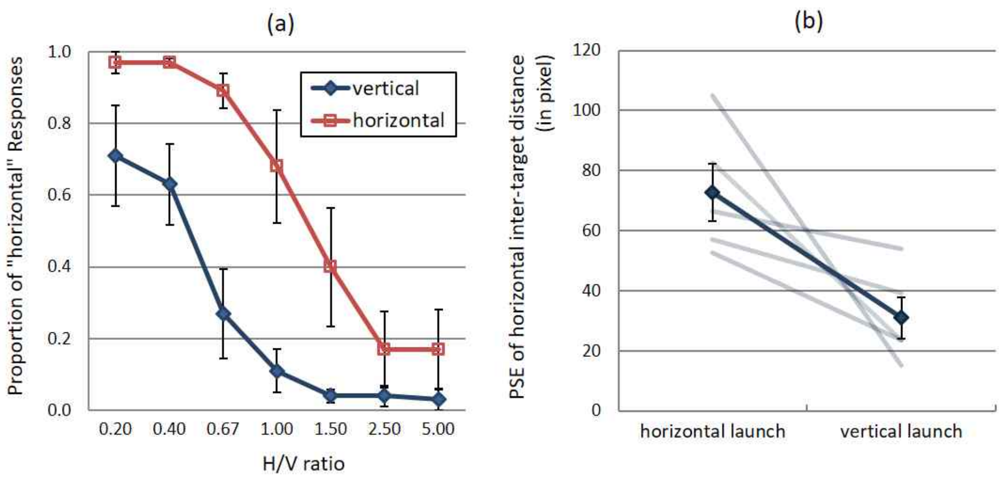

Figure 3. Results of Experiment 1. (a) Proportion of "horizontal" responses as a function of H/V ratio and display type. Error bars in this and all following graphs represent ± one standard error. (b) Individual and group mean PSEs (points of perceived equality) of the horizontal distance (in pixels). Gray lines indicate each participant's PSEs for each display type, while the black line indicates the group mean.

displacement of the context object to a collision with the motion target (Kim et al., 2013; Michotte, 1946/1963), which in turn biased otherwise ambiguous motion in a way consistent with the direction of the implied launch.

Experiment 2

The horizontal- and vertical-launch displays employed in Experiment 1 differed in the direction of implied causal collision, but they also differed in other lower-level factors correlated with the perceived collision, such as the positions of moving context objects and their motion directions. These differences might raise an alternative explanation of the contextual modulation that it did not actually influence perceived causality but instead primed the perceived direction of target motion. Motion priming typically occurs when the perceived direction of a directionally ambiguous stimulus is influenced by the moving direction of the preceding or concurrently presented stimulus (e.g., Anstis & Ramachandran, 1987; Pantle, Gallogly, & Piehler, 2000; Pinkus & Pantle, 1997). In contrast, by the nature of our display setup, the percept of target motion was affected by the adjacent context objects' motion that occurred afterward, which might suggest that the result of Experiment 1 is different from typical motion priming. Nevertheless, since back-and-forth motion of context objects repeated several times during a whole motion sequence, there is still the possibility that context motion seen in a previous cycle of a motion sequence could have biased the direction of target motion in the subsequent cycle.

To isolate the causal effect beyond the lower-level motion priming effect, Experiment 2 tested two new displays in which not only the context object adjacent to each motion target, but also the other one located on the same side of the motion quartet's imaginary rectangle, moved together in synchrony (Figures 2c and 2d). In this situation motion priming should be stronger because the number of primers were doubled, but the causal percept should be weakened because context object pairs moving together are likely to be grouped together, and their common motion is not well accounted for by a collision with a motion target. If the context effect observed in Experiment 1 was simply the result of priming, these displays were expected to elicit it more frequently than, or at least as frequently as, the launch displays did. However, if there exists an independent contribution of causality, the motion bias was expected to be significantly reduced.

Method

The same six observers from Experiment 1 participated in Experiment 2, which was identical to Experiment 1, except as noted here. We tested two new displays, as in Figures 2c and 2d. The horizontal-common-motion display was identical to the horizontal-launch display in Experiment 1, except that not only the context object immediately next to each target but also the other context object on the same side of the motion quartet moved laterally and reverted to their original positions together in synchrony.[1)] Thus, context object pairs located on left and right sides appeared to move sideways forming a mirror-symmetric motion pattern through time. In the vertical-common-motion display, context object pairs located above or below the motion targets were displaced upward or downward respectively, and then returned to the original positions. All the temporal factors of the motion sequence were identical to those in Experiment 1.

Results and discussion

As depicted in Figure 4a, participants perceived horizontal motion more often when viewing the horizontal common-motion displays (M = .51) than when viewing the vertical common-motion displays (M = .40), but this difference did not reach a significant level, $F <$ 1. A main effect of H/V ratio was significant as in Experiment 1, $F(6, 30) = 32.11$, $p < .001$, $\eta_p^2 = .865$, but a display type by H/V ratio interaction was not, $F < 1$.

The mean PSE was 66.6 pixels (1.25 of H/V ratio, SE = 10.0) for the horizontal-common-motion displays and 49.6 pixels (0.70 of H/V ratio, SE = 7.3) for the vertical-common-motion displays, but this difference was not significant, $t(5) = 1.06$, p = .338, d = .43.

If the influence of context events observed in Experiment 1 was simply due to motion priming, we should have found a significant difference between horizontal and vertical common-motion displays where motion priming was expected to be stronger than for launch displays used in Experiment 1. The nonsignificant difference can be interpreted that grouping of context object pairs by common motion generated the impression that context objects moved independently from target motion, which weakened the causal percept. This interpretation suggests that causal binding of two adjacent objects' motion was critical for perceiving target motion consistent with the direction of context motion.

To confirm this interpretation, we compared directly the PSE difference between vertical- and horizontal-event displays obtained in Experiments 1 and 2. A paired t-test showed that the PSE

1) this manipulation was motivated by Michotte's (1946/1963) camouflage studies (experiments 20 and 21).

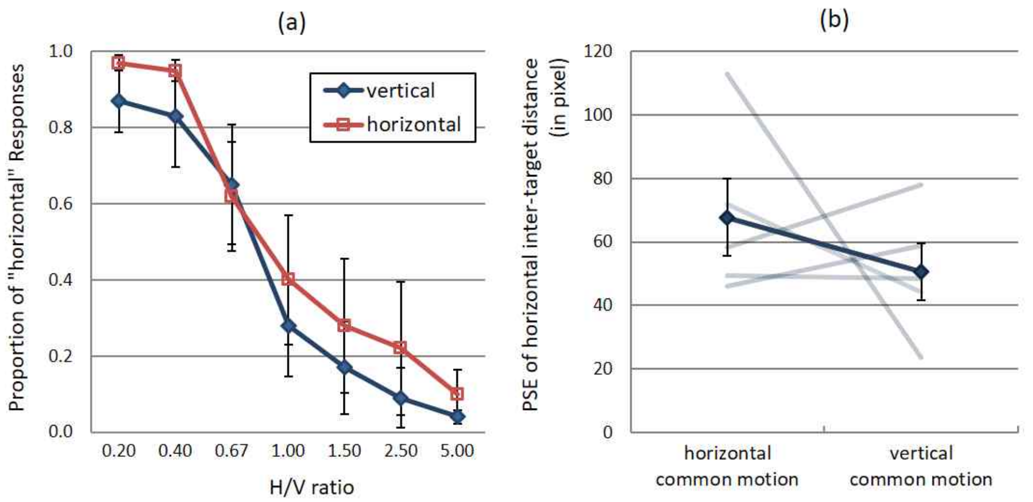

Figure 4. Results of Experiment 2. (a) Proportion of “horizontal” responses as a function of H/V ratio and display type. (b) Individual and group mean PSEs (points of perceived equality) of the horizontal distance (in pixels).

difference between the horizontal and vertical displays in Experiment 1 was significantly greater than that in Experiment 2, $t(5) = 4.05$, $p = 0.01$, $d = 1.65$, implying that the results from Experiment 1 were not completely explained by motion priming, but at least some portion of the contextual effect is a causal effect.

General Discussion

In the current study, unlike most previous studies of causal perception which used objects undergoing continuous motion, we took advantage of bistable apparent motion as a useful tool to examine the effects of perceived causality on the underlying motion process. The observed modulation of apparent motion by the contextual events suggests that the visual system might construct apparent motion that is consistent with physical regularities of mechanical causality: the target onset which is accompanied by the context object’s displacement actively signals to the visual system that the displacement is caused by the synchronized target onset, and that the actual force driving the context object’s motion comes from the opposite side, biasing motion correspondence. The current result is complementary to Kim et al.‘s (2013) study which found a bias in the perception of the trajectory of apparent motion towards the direction of the causal launch: Causal perception can influence both motion correspondence and path determination processes.

Our findings are in line with the idea that causality warps visual perception of dynamic events, reducing ambiguities in the visual processing (Buehner & Humphreys, 2010; Eagleman & Holcombe, 2002; Scholl & Nakayama, 2002). Conventionally, causality has been regarded as a form of high-level cognitive processing that occurs after low-level perceptions, such as motion contiguity in space-time. However, consistent with recent studies (Bechlivanidis & Lagnado, 2016; Buehner & Humphreys, 2010; Kim et al., 2013; Scholl & Nakayama, 2004), our findings indicate that perceived causality is not merely a summary explanation of motion events, but may fundamentally contribute to the disambiguation of impoverished sensory data.

Moreover, consistent with the previous studies (Buehner & Humphreys, 2010; Choi & Scholl, 2006; Kim et al., 2013), our research implies that the influence of causal interpretation on apparent motion correspondence can be postdictive. In a physical collision, the motion of the launching object necessarily precedes that of the launched. As Newtonian mechanics predicts that the launched object should move straight ahead if their centers of mass aligned, causal impression is weakened when the launched object veers off the straight (e.g., Buehner & Humphreys, 2010; Michotte, 1946/1963) (Figure 5a). In our launch displays, on the other hand, the motion targets (launchers) appeared before the adjacent context objects (launched objects)' displacement, and thus the task of the visual system might be to construct the most likely preceding cause event (i.e., the most plausible colliding object motion) which explains a given

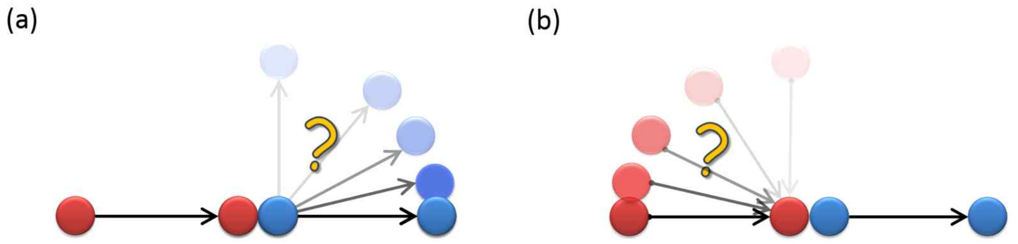

Figure 5. Schematic comparison of the perception of real world collisions and the launch display in Experiment 1. To generalize our manipulations of vertical and horizontal context events, intermediate cases of the motion events were interpolated, and the degree of transparency describes (un)likelihood of each motion event. (a) In a real collision, the direction of the launched object (blue) motion is predicted from the preceding launcher (red)'s motion that it should move straight ahead rather than veer off the straight. (b) In our Experiment 1 (e.g., in a horizontal-launch display), the motion of the launcher (red motion target) was affected by the direction of subsequent motion of the launched object (blue context object), such that the launcher's motion giving a continuity to the launched was more likely to be seen than that orthogonal to the trajectory of the launched.

follow-up effect event (i.e., the context object's displacement): the launcher's motion giving a continuity to the launched is more likely to be seen than that orthogonal to the trajectory of the launched (see Figure 5b). This indicates that the percept of causality actually retrospectively determines the low-level motion interpretation itself, rather than being a later "cognitive" interpretation.

To summarize, in line with the growing body of literature on the downstreaming effects of higher-level visual features such as animacy (for a review, see Scholl & Gao, 2013) and causality, our study suggests that the perception of causality is an earlier and more pervasive phenomenon than previously understood. That is, apparent causal relations among visual items are not merely a summary interpretation imposed upon motions already determined by perceptual processes, but rather may make a potentially fundamental contribution to the disambiguation of the underlying sensory signal itself.

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지각된 인과성이 애매한 가현운동 지각에 미치는 영향

김 성 호 정 예 은
이화여자대학교 심리학과

물리적 세계의 역동적 변화를 이해하기 위해서는 물리적 사건을 인과적 관계로 해석하는 것이 필요하다. 인과성 지각에 대한 선행 연구는 세상의 인과적 구조가 때로는 직접적으로 지각가능함을 보여준다. 본 연구는 수직 혹은 수평 움직임으로 지각 가능한 "네 물체 움직임" 패러다임을 이용하여, 지각된 인과성이 애매한 가현운동 지각에 미치는 영향을 살펴보았다. 가상 사각형의 두 대각 귀퉁이에 번갈아 제시되는 가현운동 표적 물체가 두 쌍의 맥락 물체와 함께 제시되었다. 각 쌍의 표적 물체가 나타날 때마다 인접한 한 쌍의 맥락 물체가 수직 또는 수평 방향으로 이동하면, 물체 간 "충돌" 해석과 일관되는 방향으로 표적 물체의 움직임이 경험되는 편향이 관찰되었다. 본 연구는 (1)인과성 지각이 가현운동의 대응 문제 해결에 기여할 수 있으며, (2)시간 순서상 후행사건인 맥락 물체의 이동이 선행사건인 표적 물체의 움직임 방향에 영향을 주는 사후해석적인 방식으로 가현운동이 지각됨을 보여준다. 이 현상은 인과성 지각이 물체 움직임 정보를 기초로 한 일방향적 시각 처리과정의 최종 단계가 아니며, 기초적인 운동 지각과정에 하향적으로 기여할 수 있음을 시사한다.

주제어 : 인과적 지각, 가현운동, 움직임 대응문제, 사후추정