Causal Action: A Fundamental Constraint on Perception of Bodily Movements

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Abstract

Human actions are more than mere body movements. In contrast to other dynamic events in the natural world, human actions involve mental processes that enable willful bodily movements. We reported two experiments to demonstrate that human observers spontaneously assign the role of cause to relative limb movements, and the role of effect to body motion (i.e., the position changes of the body center of mass) when observing actions of others. Experiment 1 showed that this causal action constraint impacts people's impression on the naturalness of observed actions. Experiment 2a/b revealed that the causal constraint guides the integration of different motion cues within a relational schema. We developed an ideal observer model to rule out the possibility that these effects resulted from the learning of statistical regularity in action stimuli. These findings demonstrate that causal relations concerning bodily movements play an important role in perceiving and understanding actions.

Keywords: causation; causal asymmetry; biological motion; limb movement; body motion

Introduction

Human actions are more than mere body movements. In his *Philosophical Investigations*, Ludwig Wittgenstein (1953, p. 161) posed a famous question: "What is left over if I subtract the fact that my arm goes up from the fact that I raise my arm?" This question highlights the special status of the actions of a human being relative to other dynamic events in the natural world—human actions involve mental processes that cause willful bodily movements. For example, we see rhythmic stepping forward on the ground as causing the forward motion of the agent's body; we see lifting and quickly swinging arms as causing a basketball to launch by throwing it. These types of interaction between active body movements and the distal world gives us direct experience of cause-effect relations. Thus "to step up by lifting one's leg" is properly considered to include the objective content of an action: it involves a causal structure in which moving one's limbs in a certain way provides a means to cause position changes of the body such that the intentional goal of the action is fulfilled.

We often have a strong sense of causality as actions unfold. Observing certain limb movements triggers the expectation of changes in body position. The causal link between the two types of motion is manifested in most observed human actions in our daily life (Thurman & Lu, 2014), yet in some situations this relation can be violated. A striking example is the renowned "moonwalk" dance move, popularized by Michael Jackson decades ago, in which the dancer appear to be making the physical movement of walking forwards, but actually his body moves backwards. We hypothesize that the dance movement's impact on an observer reflects the surprise triggered by its violation of a fundamental expectation about causal actions—the assignment of the role of cause to relative limb movements, and the role of effect to body motion (i.e., the position changes of the body center of mass). Although this proposal appears intuitive, no direct evidence has established that this causal constraint on bodily movements influences perception of human actions (Thurman & Lu, 2013). It is by no means obvious that human observers are sensitive to the physical causal mechanisms that govern the actions of others. Demonstrating such sensitivity to human actions is challenging because in human actions, intention, causality and perceived body movements are entangled. To resolve this difficulty, the present study experimentally separated two types of motion cues involved in actions: relative limb movements (with reference to body-centered coordinates) and the position changes of the body center of mass (with reference to distal world coordinates). This separation makes it possible to determine whether people consider the systematic relations between the two types of motion cues to be causal, or merely an associative correlation.

The present study was inspired by a ubiquitous feature of causation highlighted by Hume (1739/1888): the temporal priority of a cause to its effect. The constraint that the causal relation is asymmetric, such that effects never (or almost never) occur before their causes, is considered a necessary condition to be explained by any adequate theory of causation (Price, 1992; White, 2006). In the context of action observation, if humans assign the cause role to limb movements, and the effect role to the position change of the body (i.e., body motion), we would expect that the relative temporal relationship between limb movements and body motion will be an important determinant of action perception. In the present paper, we report three experiments to investigate the role of causation in action perception.

Experiment 1

In accord with the general causal asymmetry based on temporal priority, we hypothesized that introducing a temporal lag of limb movements relative to changes in body position (i.e., a situation in which the expected causal cue occurs after its expected effect) would signal a strong violation of the anticipated causal relation between the two motion cues. Observers are therefore likely to detect the inconsistency between the two motion cues and to judge the observed action as unnatural or artificial. In contrast, when limb movements (causes) are displaced forward in time so as to occur moderately early relative to body motion (effect), observers may show more tolerance to such misalignment (since the temporal relation between relative limb movements and body movements will still be qualitatively consistent with normal causal directionality). To examine the role of causal relation between relative limb movements and common body motion in perceiving the validity of observed actions, Experiment 1 was designed to measure how temporal offsets between limb movements and body motion impact the perceived naturalness of actions.

Methods

Participants

One hundred online participants were recruited through Amazon's Mechanical Turk.

Stimuli

Action stimuli were generated from the CMU motion-capture database (http://mocap.cs.cmu.edu) and processed using the Biological Motion Toolbox developed by van Boxtel and Lu (2013). We selected actions in which a person walked on an uneven surface with steps, with both horizontal and vertical body motion included in the sequence.

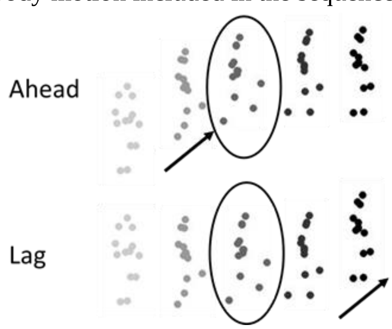

Figure 1: An illustration of different temporal relationships between body motion and limb movements.

The relationship between limb movements and body motion was manipulated by shifting the temporal sequence of common body motions forward or backward in time relative to the sequence of limb movements, as illustrated in Figure 1. Common body motions were made to either precede or lag behind the posture change resulting from the relative limb movements. The temporal sequence of body positions was shifted forward relative to limb movements in the "ahead" condition (i.e., effect precedes), and were shifted backward in time in the "lag" condition (i.e., cause precedes).

Procedure

Participants were first presented with a cover story as following: "Imagine you are viewing a walking sequence on the uneven surface with invisible steps through a slowly rotating camera. The rotation of the camera will help you perceive the 3D space. Look at the relative limb movements of the actor. Look at how the body position changes over time. Ask yourself if that could be a real person's motion in the environment. " Participants were asked to rate the naturalness of videos on a 1 (unnatural) to 5 (natural) scale.

On each trial, an action sequence was presented with a point-light walker on a checkerboard surface with invisible steps was presented. The viewpoint rotated clockwise with a speed of 3 degrees/second, aiming to facilitate a 3D perception of the biological motion stimulus in the environment. Each video lasted about 8 seconds and was played automatically with the start of each trial.

Six temporal offsets between limb movements and body motion were used: 0, ±0.5, ± 1 and 8.33 s. The 0 and very large offset (8.33 s) conditions served as extreme cases to help participants anchor the two ends of the rating scale.

The experiment consisted of 24 experimental trials, plus two attention check trials randomly placed in the experiment. An attention check trial involved a simple task, in which participants were presented with either a walking or jumping sequence, and were asked to identify the presented action. The purpose of including these two trials was to identify outlier participants who gave random responses in the online experiment. The total running time of the experiment was less than 10 minutes.

Results

Given that the participants were recruited online, we included three criteria to remove obvious outliers, including the failure of passing the two attention-check trials, or the average naturalness rating in the zero-offset condition (i.e., action sequence generated from the raw motion capture data) was lower than 2 standard deviations below the mean, or they gave the same naturalness rating value for all trials in the experiment. Nine out of 100 participants were removed according to the exclusion criteria.

The average naturalness rating for the zero-offset condition (i.e., perfect synchrony between limb movements and body motion) was the highest (M = 3.88, SD = 0.74); and the naturalness rating for the extreme offset condition of 8.3 seconds was the lowest (M = 2.28, SD = 1.02), suggesting that human observers utilized information about the magnitude of temporal offsets between limb movements and body position changes in their naturalness judgments.

To examine how temporal offsets between the two movement cues influenced the naturalness ratings, we conducted a repeated-measures ANOVA with two within-subject factors, temporal offset magnitude (.5 vs. 1 s) and offset direction (ahead vs. lag). As shown in Figure 3, the results revealed a significant main effect of temporal offset direction, $F(1,90) = 8.66$, $p = 0.004$, $\eta_p^2 = 0.83$. Observers judged actions to be more natural if the effect of body motion lagged behind the causal limb movements, relative to the corresponding ahead condition. In other words, when the temporal displacement was qualitatively consistent with the causal direction (i.e., the causal limb movements preceded the effect of body motion), people showed more tolerance of temporal displacement than in the corresponding ahead condition (i.e., when the temporal offset was opposite to the causal direction).

We also found a significant main effect of offset magnitude, $F(1,90) = 29.13$, $p < 0.001$, $\eta_p^2 = 1.0$, indicating that people were sensitive to the temporal alignment between the two motion cues when assessing the validity of observed actions. In general, larger offsets resulted in lower ratings of naturalness. The two-way interaction between offset magnitude and temporal direction was not significant, $F(1,90) = 0.15$, $p = 0.70$.

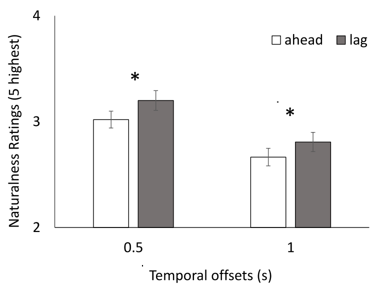

Figure 2: Naturalness ratings in the ahead condition (effect of body motion preceded) and in the lag condition (causal limb movements preceded). Error bars represent standard errors of the mean.

Experiment 2a

In Experiment 2, we aimed to create a reasoning task in which the two movement cues were represented by distinct visual entities in the display. This new reasoning task serves to assess whether people use the default causal relation to form an explicit binding between the two types of movements.

Methods

Participants

Twenty-two UCLA undergraduate students (mean age = 20.8; 16 female) participated in the experiment for course credit. All participants had normal or corrected-to-normal vision.

Stimuli

Four action sequences of an actor walking on an uneven surface were displayed from two viewing directions with orthogonal projection. The actor was made to appear to walk on a treadmill by maintaining a stationary position for the average location of two hip joints at the center of the screen. To depict the position change of the body over time, a gray dot moved according to the trajectory of body motion. Figure 3 provides an illustration of the stimuli.

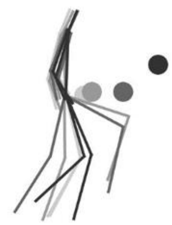

Figure 3: Illustration of stimulus for Experiments 2a and 2b. The stick-figure actor shows the posture change over time at a stationary location; the dot depicts the motion of the body. The figure and the dot change from a light color to a dark color in proportion to the elapsed time.

Procedure

Participants were first given a cover story along with illustration figures. “Imagine that you work for a specialized video analysis company and are given two sources of information: a processed video from a motion tracking system, which records a person’s posture change over time and keeps the figure always at the center, and the location of the person reported from a GPS system.” After the cover story, participants were presented with two video clips which illustrated how the posture change in a stationary location was separated from the position change of the body over time based on the original motion capture video. Note that our display explicitly isolated the effect cue, body motion (represented by the gray GPS dot) and the causal cue, limb movements (represented by the red figure). Participants were asked to decide whether the movements of the GPS dot matched the posture changes of the actor by pressing one of the two response buttons.

After receiving the cover story, participants were given two practice blocks with feedback to familiarize them with the task. Practice trials included stimuli with either perfectly aligned movements or with excessive temporal displacements (temporal offset of 8.33 s).

In the subsequent test session, 96 trials were presented to participants. The experiment included eight levels of temporal offsets between the position change of the body resulting from body motion and the posture change resulting from limb movements (±0.02s, ±0.5s, ±1s and ±1.5s, respectively). On each trial, the action stimuli lasted for 6.67 s. The first 100 frames (i.e., 1.67 s) presented only the walker, with the goal of encouraging participants to maintain fixation on the walking action. Then the GPS dot appeared at the center of screen in the 101th frame, and subsequently started to move according to the assigned trajectory of body motion. The test block included four viewpoints (45^o, 135^o, 225^o and 315^o), and each viewpoint was tested three times under each of the eight offsets. The order of conditions was randomized.

Results

The results of Experiment 2a are shown in Figure 4. A repeated-measures ANOVA with two within-subject factors (ahead vs. lag condition, and four temporal offset levels) revealed a significant main effect of offset magnitude, $F(3,19) = 37.83$, $p < 0.001$, $\eta_p^2 = 1.0$, indicating that participants were sensitive to the temporal offsets between the two motion cues in this explicit binding task. Importantly, the interaction of offset magnitude and temporal direction of offset was significant, $F(3,19) = 4.51$, $p = 0.015$, $\eta_p^2 = 0.80$, indicating that the influence of causal direction of the two movement cues on the binding judgment depended on the magnitude of temporal displacement introduced into the stimuli. Specifically, when the temporal offset was very large (e.g., 1.5 second), observers presumably considered the posture change of the walker and the GPS dot movements to be generated from different sources, and therefore judged them as mismatched signals, regardless of the temporal direction of offset. Similarly, when the temporal offset was very small (e.g., .02 second), observers may not have detected the difference in temporal directions, and thus also did not show a temporal asymmetry effect. Hence, the critical testing offset conditions were the middle range and we did planned comparisons for ±.5 and ±1 second conditions respectively. Indeed, we found that with a 1 s offset, the lag condition (M = 0.44, SD = 0.29) yielded a significantly higher proportion of matched responses than did the ahead condition (M = 0.29, SD = 0.25), $F(1,21) = 9.69$, $p = 0.005$, $\eta_p^2 = 0.84$. Thus a causal asymmetry effect was observed within a middle range of the temporal window, when the two motion cues could be interpreted as originating from a single actor.

In summary, Experiment 2a used an explicit binding task to provide converging evidence that observers are sensitive to the temporal relation between limb movements and body motion. The two motion cues were more likely to be judged as matched when the causal limb movement preceded the effect of body motion, in comparison to when the effect cue preceded the cause. This temporal asymmetry effect supports the hypothesis that human observers naturally assign the role of cause to relative limb movements and the role of effect to body motion (i.e., they expect limb movements to cause changes of body position in the environment).

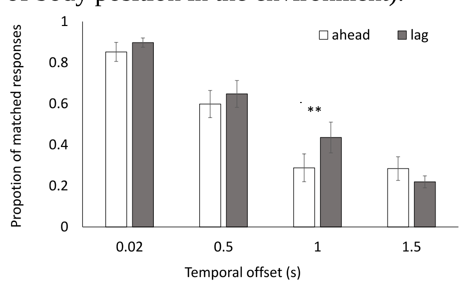

Figure 4: Results of Experiment 2a. The proportion of “matched” responses in the ahead condition (GPS dot shifted ahead of limb movements) and in the lag condition (GPS dot lagged behind of limb movements).

Experiment 2b

If the temporal asymmetry effect found in previous experiments was resulted from the observers’ understanding of the causal relation between the two motion sources, then the effect should be radically altered when the causal relation is changed. Experiment 2b aimed to measure differences in people’s pattern of judgments attributable to the influence of the causal interpretations conveyed by the cover story.

Participants

21 UCLA undergraduate students (mean age = 20.2; 19 female) participated in the experiment for course credit.

Stimuli and Procedure

We used stimuli identical to those of Experiment 2a, but changed the cover story so as to reverse people’s understanding of the causal relation between posture change and dot motion, by specifying that the dot represented a moving laser spot that the person aimed to follow. In this situation, the two components of the stimuli are interpreted as representing two distinct entities, such that the laser spot is the cause that makes a person move in certain ways (i.e., the limb movements are the effect). Participants were instructed to judge whether the person succeeded in following the laser spot. All other procedural aspects were identical to those in Experiment 2a.

Results

The results of Experiment 2b are shown in Figure 5. A repeated-measures ANOVA revealed that the interaction of offset magnitude and temporal direction of offset was significant, $F(3,18) = 38.54$, $p < 0.001$, $\eta_p^2 = 1.0$. When the dot motion preceded body movements in the ahead condition, participants judged the actor to be successful in following the dot, regardless of the magnitude of temporal offset, $F(3, 18) = 6.71$, $p = 0.003$, $\eta_p^2 = 0.94$. However, when dot motion followed body movements in the lag condition, the temporal misalignment magnitude significantly impacted human judgments, $F(3, 18) = 62.13$, $p < 0.001$, $\eta_p^2 = 1.0$. When the proportion of “success” responses in the ahead condition was subtracted from the corresponding proportion in the lag condition, the difference was significantly below zero for temporal offsets of 0.5 s, 1 s, and 1.5 s (all *p*s < 0.001), indicating a higher proportion of success responses when the dot motion (cause) preceded the body movements (effect), relative to the corresponding condition in which the effect cue preceded the cause.

These results imply that when observers received a cover story in Experiment 2b that reversed their interpretation of the cause-effect relations between moving objects (i.e., moving dot as cause and limb movements as effect), their judgments changed dramatically. Observers were more likely to judge the action to be successful in following the laser spot when the dot motion was shifted forward relative to limb movements. Furthermore, this temporal asymmetry effect was maintained for a large range of offset magnitudes (from .5 s to 1.5 s). The strength and robustness of the effect is likely due to people’s qualitative interpretation of a “following” action: this relation is granted as long as the movement of one object follows the same trajectory as that of another object. Whereas the causal relation between limb movements and body motion of a single agent (Experiments 1 and 2a) is closely coupled in time, the action of an agent that is following a separate object (Experiment 2b) can be much more temporally variable, as long as the motion of the agent lags behind that of the object.

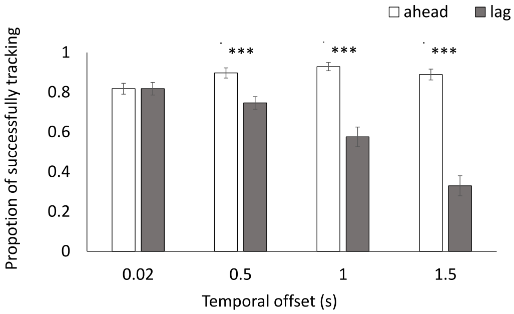

Figure 5: Results of Experiment 2b. The proportion of reported successful tracking responses in the ahead condition (laser dot was shifted ahead of limb movements) and in the lag condition (laser dot lagged).

An Ideal Observer Model

To further assess whether the temporal asymmetry effect could possibly be explained by statistical regularity in walking actions, rather than causal relations between two movement cues, we developed an ideal observer model solely based on visual statistics of action stimuli. The observer model is a hypothetical device that makes optimal decisions given available information based on natural statistics of the visual environment (Geisler 2011; Kersten, Mamassian & Yuille, 2004; Lu & Yuille, 2006). To capture the natural statistics in relevant action stimuli, we analyzed 20 walking actions (each consisted of 1500 frames) from the CMU motion-capture database, in which an actor explored an indoor environment with uneven surfaces. We generated a pool of point-light stimuli from 20 actions each viewed from six different directions with orthogonal projections. This stimulus set included a total of 180,000 posture frames (20*1500*6). To quantify body motion, the velocity was calculated as the position change of averaged hip joints from a frame to its neighboring frame. To reduce the number of postures resulting from limb movements in walking action, a K-mean algorithm (Jain, 2010) was employed to categorize the posture frames into a smaller number of key postures. Twenty key postures were selected since the sum of error reached a plateau after 20 clusters, indicating that adding more key postures did not improve the clustering performance. Each frame in the stimulus set was assigned to the most similar key posture as the corresponding label. Using all this information, we computed the histogram of velocity of body motion for each of the 20 key posture, and fitted the histogram using a 2D Gaussian distribution to estimate the mean and the covariance of common body motions given a key posture, as illustrated in Figure 6.

To simulate the judgment in Experiment 2a, each posture frame in an experimental trial was first assigned to the most similar key posture, and subsequently to the associated distribution of body motion. The displaced body motion in the input was mapped to the corresponding distribution to derive a likelihood. Finally, log-likelihood was calculated by summing up each frame's likelihood in the log scale for each stimulus. Figure 6 (right) shows the simulation results. Higher log-likelihood values indicate greater probability of considering the two motion cues as "matched". The ideal observer model consistently predicted more matched responses in the ahead conditions compared with the lag conditions, which is opposite to the temporal asymmetry effect observed in Experiment 2a. The ideal observer model (which lacks any causal constraint) thus failed to account for the pattern of human judgments. The failure of the model based solely on visual statistics shows converging evidence that causal understanding of body motion provides a critical constraint used by human observers in deciding whether perceived motion is natural.

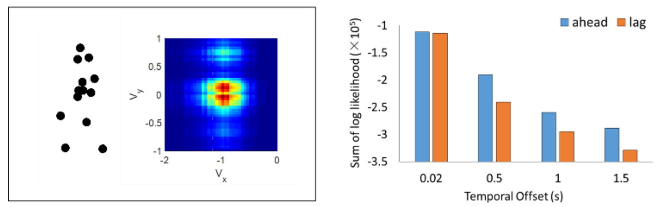

Figure 6: Results of an ideal observer model based on visual statistics. Left, body motion distribution associated with a key posture frame, derived from visual statistics from walking action observations. Right, the model simulation results for Experiment 2a, which is opposite from human results, suggesting that association between limb movements and body motion learned from visual statistics is insufficient to account for human performance.

General Discussion

The present study provides evidence for both perceptual and inferential processes involved in causal action judgments. Experiment 1 revealed that actions with preceding limb movements were rated as more natural than those with preceding body motion. This result suggests that people adopt the directionality of causal relation between limb movements and body motion when judging the naturalness of observed actions, despite this perceptual task appears not to explicitly require the sensitivity to causal relation between the two motion cues. The results of Experiment 2 collectively revealed that when considering movements attributed to a single actor (Experiment 2a), by default the brain binds bodily movements of articulated limbs (causes) to moving body locations in the environment (effects). However, when considering movements of one agent with respect to a separate distal object (Experiment 2b), the brain can flexibly assign the effect role to bodily movements of the agent, suggesting the involvement of the inferential process in causal action judgment. Thus people form a causal understanding of what drives perceived actions, which in turn influences their judgments of action naturalness.

The present findings both support and extend the large body of research on causal perception and inference. Seminal work on causal perception (Michotte, 1946/1963), coupled with contemporary developments (Scholl & Tremoulet, 2000; White, 2006), has illuminated the mechanisms by which humans directly perceive the causal structure of the visual world. It is possible that a primitive psychological concept of causation may develop by extension from the fast, automatic and irresistible visual impression of causality arising from simple kinematic events. However, previous studies of causal perception have mostly involved simple displays of moving objects with rigid shapes. The present findings extend research on the interactions of objects (such as colliding balls) in the physical world to agent-related body movements. Thus, the paradigm introduced here (using action stimuli with whole-body movements) opens the door for further experimental investigations directed at the interface between causal perception and inference.

Actions afford privileged access to experience the role of agency, and hence provide a powerful tool to produce interventions that in turn help to discover causal relations in the physical and social environment (White, 1999). Numerous studies have shown that action perception is an active process, in which humans automatically predict actions to project the future course of an activity (Flanagan & Johansson, 2003; Graf et al., 2007; Prinz, 2006). Our study highlights the importance of causal interpretation in perceiving body movements. As relational binding in general enhances representational power (Lu, Chen & Holyoak, 2012), the perceived causal relation between the two movement cues enables people to understand why the body moves the way it does. The present study is limited to the simplest causal action, in which a single causal link exist between limb movements and body motion. The future investigations in causal action need to consider background cause (i.e., gravity) or other potential causal cues (i.e., body motion is caused by a moving skateboard). These situations open the door for.

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