Editor: Gerd Graßhoff, Bern
Co-editors: Timm Lampert, Bern; Tilman Sauer, Bern

Michael May:
Interdisciplinary Perspectives on Causation / edited by Michael May and Uwe Oestermeier. – Bern, 2001.

ISBN 3-8311-2162-1

Herstellung: Books on Demand GmbH

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VISUAL CAUSALITY

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ABSTRACT

Human operators are required to cope with increasingly complex artificial systems. The way in which they function causally is often poorly understood. We determine the basic problem to be that of a widening gap between actual and perceived causality. The present chapter systematically uncovers this gap and provides some solutions from the perspective of theories of human perception. A phenomenological analysis of the perception of causality was first tackled by Heider and Simmel (1944) and was later completed by Michotte (1946/63). This analysis is still popular and is based on the assumption that we have direct access to the perception of causal relationships. However, more recent investigations have shown that the impression of causality is not always tied to the narrow spatiotemporal boundary conditions described by Michotte, and that our causal impressions may be at odds with actual causal relations. For instance, our perceptions of causal relations in ballistic movements are distorted and may even be contrary to the actual causal relation. We present an account of the perception of causality that takes a different view on the question of why we perceive events to be causally related. According to this view, the biodynamics of our effectors and the control of our actions provide the framework for the perception of causality.

INTRODUCTION

The accelerated deployment of complex tools ranging from a TV remote control to television-supervised surgery (see Satava, 1997) is characterized by a growing gap between perceived and actual cause-effect relations. These hi-tech tools have far-reaching consequences for our perception of how human actions are related to environmental effect. Apparently very dissimilar objects have to be causally related. Whereas our ancestors had to pull a mechanical lever to set a switch – with the causal agent (the Aristotelian causa efficiens) plainly visible via the pivot point –, we are merely required to perform a mouse click on a colored symbol on the computer monitor. A host of further examples could be pointed to support the view that modern civilization provides growing challenges for our perception of causality. In particular, we have to bridge a rapidly expanding gap between the visible cause of our actions and their visible effect in order to continue to perceive the nexus.

In this contribution, we would like to complement the established view that the perception of causality is both unmediated and direct. To this end, we will proceed by sketching a conceptual framework building on a tight connection between the concept of intentionality and the concept of causation. Both extrinsic and intrinsic intentions play a role. Far-reaching conclusions for the acquisition of causal relationships in artificial environments have to be drawn from these insights.

THE PHENOMENOLOGY OF CAUSALITY

Since Hume, philosophers have focussed on understanding the concept of causality as a causa efficiens. In terms of scientific explanation, a cause is an event that is sufficient to give rise to a second event. For instance, the collision of a moving ball with a stationary one is the cause for the subsequent motion of the latter object. David Hume (1740/1978) assumed that causality is inferred from the repeated association of two events. In this associative concept of causation the mere coincidence of two events suffices to evoke the impression that the temporally later event is the effect of the temporally prior event. In addition to the temporal succession – which leads to the impression of a causa efficiens according to Hume – one may assume additional mechanisms between colliding motion and ricochet motion that further describe the causal relation (friction, energy transfer, etc.).

In contrast to the associative concept of the causality favored by Hume, Michotte (1946/63) put forth a fundamentally different concept. Michotte claimed that we have acquired efficient perceptual devices for mechanic causation that allow us to directly perceive causality. According to Michotte, the perceptual impression of causality is formed without conscious or unconscious inferences (see Helmholtz, 1894, on this topic), and does not require learning. Observers see a causal relation in an unmediated fashion and do not require supplementary knowledge for this impression.

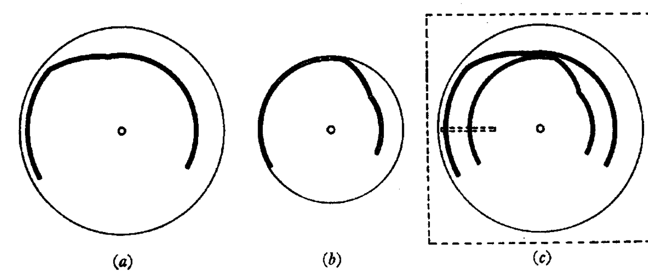

Fig. 1. Disks used by Michotte.

Figure 1. Disks used by Michotte. On one side of the disk, a horizontal slit (visible in c) created a view-port. In this view-port, the lines were perceived as small rectangular objects. When the disks were rotated, the objects appeared to move as soon as the radius of the trace changed.

In accordance with this hypothesis, Michotte (1946/63) was able to demonstrate that observers perceive the motion of two simple objects as causally related if particular boundary conditions are met. Michotte did most of his experiments with a disk covered by a mask except for a small slit which served as a view-port (see Figure 1). The two circular lines observed through the view-port were perceived as approaching and receding objects. In his investigations, he used different line drawings, that is, different curvatures, so as to manipulate the temporal and spatial parameters of the object motion. Despite the artificial nature of the stimuli generated with this method, a stable impression of causality could be produced.

By and large, Michotte focussed on two possible combinations of two objects. In the so-called "entraining effect" object A moved toward a stationary object B and, as soon as object A reached object B, B started to move. The two objects then started to move in the same direction, yielding the impression of B drawing A with it. The "launching effect" is very similar, except for Object A remained motionless after having made contact with object B. The launching effect may be observed in a realistic setting when two billiard balls of equal weight collide with their centers of gravity aligned.

NECESSARY BOUNDARY CONDITIONS FOR THE IMPRESSION OF CAUSALITY

Particular spatial and temporal relations between two objects are necessary for creating a convincing impression of causality. The insertion of a gap of a particular size between objects A and B changes the nature of the perceived event: Instead of reporting an impression of causality upon viewing the displays, observers see the first movement triggering the second movement. Although one may still conceive of triggering as a causal relation, the impression is weak compared to the launching effect. In addition to the spatial conditions that have to be met for the impression of causality, temporal parameters are crucial. Consistent with Hume's ideas, Michotte reports that a temporal delay of the second motion, that is, a disruption of the temporal coincidence, leads to an immediate loss of the causal impression. In sum, both spatial as well as temporal separation of the two movements result in a reduction of the impression of causality.

However, subsequent investigations produced results that which did not conform to the notion that causality is an original and immediate perceptual quality. For instance, judgements of causality change depending on the perceptual attitude and experience of the observer. Observers who adopt an analytic attitude tend to describe the collision

event in the sense of Michotte as a sequence of independent movements, and not as cause and effect (Beasley, 1968, Gemelli & Cappellini, 1958). Similarly, there is a tendency to adopt more rigid criteria for what is considered to be a causal event after a series of prototypical examples of causation have been observed. Conversely, the observation of poor examples (in the sense of non-prototypical events) enlarges the number of events judged as causal. That is, thresholds for the perception of causality can easily be raised or lowered (Gruber, Fink, & Damm, 1957; Powesland, 1959).

Moreover, there is evidence that spatial proximity is not a necessary requirement for perceiving cause and effect. Houssiadas (1964) ran a large number of experiments in which he introduced spatial and temporal discontinuities. In Figure 2, one of his experiments is sketched. A circle moves toward a rectangle, but the objects do not touch. The deformation of the rectangle is perceived to be caused by the circle although the circle does not touch the rectangle, in fact, it does not even come close to the space previously occupied by the rectangle. This finding is surprising, as Michotte (1946/1963) argued that perceived causality only occurs with strong temporal and spatial coincidence.

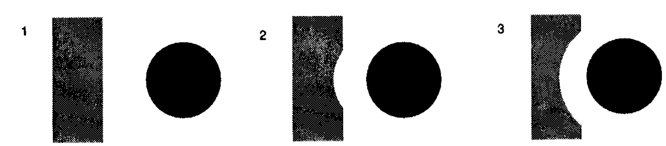

Figure 2. The motion of a circle towards a stationary rectangle. Figures 1-3 are presented successively. The observer has the impression that the motion of the circle causes the deformation of the rectangle.

EVIDENCE OF DIRECT PERCEPTION OF CAUSALITY

Thus, Michotte's goal of describing the spatio-temporal boundary conditions for the perception of mechanical causation turned out to be more complex than his original work may have suggested. The visual system accounts for individual experience and attitudes, as well as particular classes of events. It would appear that a uniform and parsimonious description of visual causal events is hard to achieve. Nonetheless, to reject Michotte's concept of direct perception of causality would be premature. On the contrary, one encounters his views in James Gibson's (1979) direct realist approach (1979).

With this approach, one hypothesis derived from Michotte's model, namely, that even infants should be able to perceive causality, was to a large degree confirmed. Evidence for sensitivity to the spatio-temporal properties constituting a collision event was a first point in case of the assumed ability to perceive causality in infants (Ball, 1973). Later, a specific sensitivity for causality was confirmed (Leslie & Keeble, 1987; Oakes & Cohen, 1990). Leslie and Keeble (1987) presented infants with a typical collision event in which a moving object A kicked off an initially stationary object B. After habituation to this event, infants showed increased interest for events with a reversal of the causal roles (B sets A into motion) than for events in which only the spatio-temporal properties of the sequence were modified (B moves before A but does not collide with it).

Furthermore, results gained within the framework of information integration theory (Anderson, 1981) confirmed the assumption of direct perception of causality. Schlottmann und Anderson (1993) modeled individual differences in the perception of collision events by inter-individually varying weights assigned to single cues, such as temporal and spatial distance. The integration of the cues, however, followed an invariant integration rule roughly corresponding to Michotte's direct perception of causality. Further, Shanks & Dickinson (1987) rejected the hypothesis that the perception of causality is an acquired skill that does not follow common laws governing the acquisition of cause-effect relationships in other contexts. Typically, judged causality between two events, for instance, pressing a button and reinforcement, varies with the contingency of the two events. The more probable the association of the two events, the more probable is the judged causality. Accordingly, judged causality in the launching effect is expected to decrease where the collision of A with B is not always followed by B being set in motion. In this case, the motion of A may be considered a poor predictor of the motion of B. Although poor predictors typically produce low judgements of causality, this

does not appear to be the case with collision events. When the motion of object A was followed by motion of object B in only 50% of the cases, no significant drop in judged causality was observed. Even a change in the color of one of the objects that predicted the motion of object B with greater accuracy than the motion of object A had no effect on causality ratings. These findings speak against the assumption that the perception of causality in mechanical events is acquired through associative learning. In other words, the predictive value of an object does not affect the impression of causality in the "launching event". Despite opposing associative bonds, the temporal and spatial coincidence of the two movements had a strong impact on estimated causality. A behaviorist concept of causality perception, as one may ascribe to David Hume, is unable to explain these data.

Thus, a somewhat complex picture of the perception of causality emerges. On the one hand, there is an apparently innate tendency to perceive two consecutively presented motions as causally related. To produce this impressions, certain boundary conditions have to be met. In particular, cause and effect have to be closely connected both in the spatial and in the temporal domain. The perception of causation in such mechanical events is not influenced by associative contingencies – as predicted by the theory of direct causality perception (Michotte, 1946/63). However, for other types of events (e.g., key press-reinforcement), contingency plays a major role. The nativist view of Michotte is endorsed by these findings, in particular by the research on causality perception in infants. On the other hand, some studies pointing to the importance of individual attitudes and learning pose a large problem for the concept of direct causality perception.

At this point in our discussion, it would appear appropriate to ask some questions about why, in the course of human evolution, we have acquired the ability to perceive causality. It appears that on many occasions, we are ready to perceive causal relationships even though temporal and spatial contiguity is absent. This supports the notion of a strong innate tendency, maybe even the need to link almost arbitrary events. However, on other occasions, we perceive causality in a very exclusive manner. As described above, the limits of what we sense as being causal are well known. These two conflicting findings may be reconciled if the perception of causality is conceived of as an extremely plastic function of the visual system. A possible answer to the question as to what the advantages of such a flexible system may be was provided by Riedl (1992). He gave an impressive account of the way in which the human being have been structured during the course of evolution to expect significant causal relations in almost any combination of events. This strategy, he suggested, was particularly successful for discovering actual causal relationships in human evolution. In a sense, it is more economic to expect causes in places where such causal relationships turn out to be absent, rather than to miss the true causes for being too reluctant to establish a subjective causal link. Where causal relations have been confirmed, the limits for what we perceive to be causal are subsequently narrowed. In the following sections of the paper, we will focus on situations in which our need to build causal relationships leads us astray, and suggest a new hypothesis to account for these errors.

INTUITIVE PHYSICS AS THE RESULT OF A NECESSARILY BLURRED MECHANISM FOR DISCOVERING CAUSES (CAUSA EFFICIENS)

From an evolutionary point of view, one may want to argue that true causal relations have only been discovered inasmuch as they have been internalized by the perceptual system to secure the survival of the species (Riedl, 1992). Whenever erroneously perceived causal relations did not have any adverse consequences, errors were not corrected. Thus, our visual and intuitive understanding of many processes in classical mechanics is a rough approximation of Newtonian mechanics - at best. It has often been argued that our perceptual system is at the developmental stage of Aristotelian physics (e.g., McCloskey, Caramazza & Green, 1980). For instance, many observers believe that a ball rolling through a bent tube will continue on a bent path (B) once it exits the tube (see Figure 3). The straight path (A) is Newton's solution, of course. Interestingly enough, the range of acceptable events is more restrained for the visual system than it is for conscious reflections on such matters. If the visual scene in Figure 3 is animated, our judgements are closer to reality than when we are given a paper-and-pencil version of the test (Kaiser, Proffitt, Whelan & Hecht, 1992). That is, path B looks strange in a dynamic rendering,

but not with static displays. At this point, one is struck by the strong discrepancy between the perception of animated displays (which are closer to physical reality) and judgements about static trajectories (which are an integral part of physics textbooks). The same subject that erroneously selects B as a correct response in the paper-and-pencil version of the test, may consider A as the correct trajectory when the situation is simulated on a computer screen.

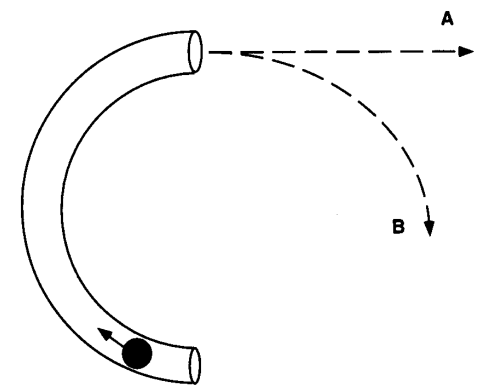

Figure 3. Imagine a marble being rolled through a narrow tube. What path does the marble follow after exiting the tube? Two possible trajectories are depicted after the ball has left the tube. Alternative B - although wrong - is frequently selected when the problem is posed with static displays. With dynamic displays, the number of errors is largely reduced.

MEMORY FOR CAUSES

Examples taken from research on intuitive physics suggest that erroneous conceptions about physical regularities have been acquired during the course of evolution, and have never been corrected. Here, it is not necessary to mention the complete failure of high school classes to remedy these deficits. In addition to the distortion of knowledge about the laws of physics, our memory distorts causal experience such as to make it consistent with (assumed) regularities in the physical world: In classical mechanics, the velocity of a stationary and a moving object of equal mass are exchanged if the two objects collide with their centers of mass aligned. The object that initially moves and collides with a stationary object comes to a sudden halt, that is, it loses its velocity, whereas the previously stationary object begins to move at the same velocity as the object that initially moved. When observers are asked to remember the velocity of an object A that sets an object B of equal size in motion, the influence of B's velocity on the representation of A's velocity was observed (Kerzel, Bekkering, Wohlschläger, & Prinz, 2000). If, in violation of the laws of physics, B's velocity is higher than A's, the remembered velocity of A will be higher than it actually was. Conversely, when compared to A, B has a lower velocity, the remembered velocity of A is reduced. Thus, it appears that observers distort the velocity of a causal motion in memory so as to be in accord with the velocity of the produced effect. This memory bias shows that we have a strong tendency to store observed events in a manner consistent with regularities of the physical world, that is, the laws of physics.

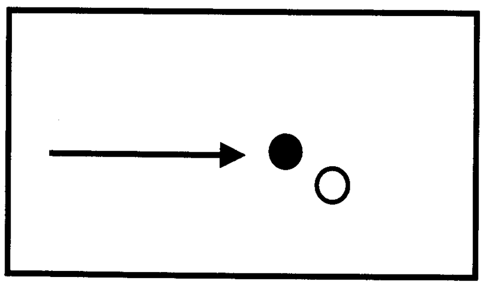

Figure 4. The arrow indicates the direction of motion of the stimulus. The filled circle shows the actual final position of the target, the open circle shows the estimated final position. Judgements systematically deviate in the direction of motion and downwards from the actual final position.

Another distortion the also follows physical regularities may be observed when subjects are asked to judge the final position of a moving object. For instance, when observers are asked to position a pointer on the last position of a stimulus that moved linearly from left

to right on a computer screen, they will not point to the actual vanishing point, rather their judgements will be systematically biased. As shown in Figure 4, judgements deviate in the direction of motion from the actual vanishing point (see Hubbard, 1995, for an overview). This distortion has been attributed to the observers' tendency to mentally extrapolate the position of a moving object while it is visible. Functionally, mental extrapolation was supposed to facilitate goal-directed actions toward moving objects. If an observer stays a little "ahead" of the target, it may be easier to grasp or catch it. As a side-effect, however, mental extrapolation cannot be halted instantaneously when the object vanishes. Therefore, the mental position at the time of target disappearance will be ahead of the actual target position. In analogy to the momentum of physical objects, Freyd (1987) coined the term "representational momentum" to refer to the inability to stop the mental extrapolation exactly at target disappearance. In addition to the distortion in the direction of motion, it was observed that the final position judged systematically deviated from the actual position downwards. This error has been attributed to the internalization of physical gravity. Future positions of a moving object are mentally anticipated according to internalized physical principles. Additional environmentally invariant factors that affect judgements of the last position of moving target are friction, mass, weight, and context (Bertamini, 1993; Hubbard, 1995).

To sum up, our representations of motion and position are strongly influenced by regularities of the physical world. Although our conceptions about physical events are not always correct, our internal physical conceptions exert a strong influence on the way in which we remember things in the world. One may conclude by saying that the internalized physical world (even if faulty) determines the mental world. The considerations of Freyd (1987) explain these blatant memory distortions by referring to the survival value of the mechanisms involved. Usually, it is very helpful to anticipate the velocities of two objects of equal size after their collision, or the future position of a moving object. Therefore, it makes sense to internalize physical principles, even if the representation is incomplete and faulty.

ERRONEOUS EXTERNAL CAUSATION

So far, one may conclude that our visual perception takes actual causal relations as a first approximation, but adds some noise in the process of internalization. For instance, a reduction of the temporal and spatial coincidence of cause and effect reduces the experience of causality. This reduction is quite consistent with physical plausibility. The mistakes occurring in intuitive physics are deviations from empirical reality, but these mistakes mirror our conceptions about the external world: Memory of velocities and position follow the laws of physics. However, there are some convincing examples of very simple situations in which the perception of causal relations does not follow internalized physical principles or their approximations. Rather, principles of self-performed actions and intentions are applied to the perception of causality: In the case of ballistic movements, an alarming number of observers believe that a projectile that has been shot accelerates after it has left the cannon. Similarly, observers judge a thrown ball that increases its speed after leaving the pitcher's hand to look more natural than a ball that decelerates in accord with physical law (Hecht & Bertamini, 2000). Figure 4 shows the median of judged maximal velocity of a ball traveling either on a curved (low velocity) or straight (high velocity) trajectory. 84 average college students served as subjects. One may ask oneself what the results would have looked like if older people – with a much longer retention interval for their last physics class – had participated. This surprising but stable finding is best explained by referring to our motor system: The acceleration of the limb throwing the ball has been projected onto the object's trajectory. In a sense, we extend what we know about our own body mechanics to externally moving objects. One may think of this as a support for a motor theory of perceived causality.

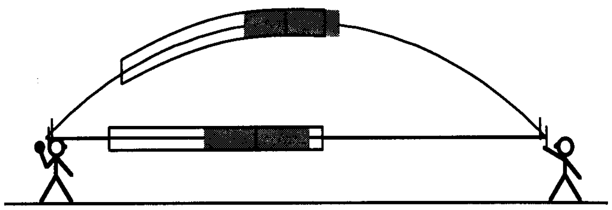

Figure 5. Subjects received two line drawings depicting a bent or straight path of the projectile. They were then asked to mark the point of maximal velocity. The vertical marker indicates the median of judged maximum velocity, the 95% confidence limit is drawn in gray, the box delimits first and third quartile.

THE EFFECTS ORGANIZE PERCEPTION AND MEMORY OF CAUSAL RELATIONS

These findings may be considered evidence in support of the hypothesis that the temporal boundary between cause (movement of the arm) and effect (flight of the ball) is blurred in our perception. In other words, perception and action are cognitive but not visual categories. This lack of discrimination is in line with the assumption of a common coding of perception and action (see Prinz, 1997). This approach goes back to the early theorizing of Lotze (1852) and Harleß (1861). They dealt with the problem of the possibility of knowing action plans at an abstract level, without detailed information about the coordination of single muscles. Given that we do not directly control the muscles involved in movement, Lotze and Harleß considered it a mystery that we are able to execute goal-directed movements at all. To solve the mystery they assumed that actions and their effects are associated during the course of an infant's development. By virtue of the temporal coincidence of muscular movement patterns (low level action patterns) and their sensory consequences, a bilateral association between actions and their effects is formed. Thus, it becomes possible to activate an action plan by first activating the cognitive representation of its sensory consequences, namely, its effect. Activation of the effect will automatically spread to the corresponding action plan via the bilateral association. In contrast to the details of action planning (the complex interaction of muscles) not accessible to conscious thought, effects of an action are accessible via sensory experience. For instance, it is not difficult to imagine the trajectory of an arm movement – in contrast to the coordination of the muscles involved. According to Lotze and Harleß, the seemingly inaccessible action coordination is achieved by means of consciously accessible information about action effects. In this concept, intended effects of an action are of large significance for action control. The activation of action effects is in a sense the only possible way of executing a goal-directed action. In the same vein, William James rephrased these ideas some time later: "We may ... lay it down for certain that every representation of a movement awakens in some degree the actual movement which is its object" (James, 1890, vol.2, p. 526). Like his German colleagues Lotze and Harleß, James believed that the thought of an action suffices to activate the action itself, once the thought has reached a certain strength. More recent studies show that this very simple-minded idea is closer to reality than one may suspect at first glance (Prinz, 1997)

In the present context, we may ask what the implications of such a model of action control may be for perception and memory. If action effects play a major role in the structure of perception and memory, then one would expect contents of perception or memory to be organized in terms of their effects. In other words, the organization of causal event sequences in memory (Kerzel et al., 2000) and perception should be effect-oriented. It seems that we build the mental images of reality in such a way that a certain fit between actions and their respective effects is achieved. Similarly, the distortion of the final position of a moving target (representational momentum) may be reinterpreted as the effects of mental analogues of physical forces. Thus, the final position of a moving target is stored so as to be consistent with the effect of such a force. Finally, an effect-oriented picture of human perception and memory predicts that the limits of actions and their effects are not always clear-cut, given that we perceive and store events based on their effects. The discovery that properties of the human motor system are projected on to beliefs about observed trajectories supports this notion. In this case, causation is

erroneously attributed to the actor for too long in a throwing event. Although the projectile has left the actors hand, it is believed that the latter continues to exert an influence on path of the projectile. The boundary between the actor's body that produced the throw, and the subsequent effect, the trajectory of the object, is blurred. One may note that for all of these observations cause and effect are outside the observer, that is, we are not talking about self-performed actions and their effects. Nonetheless, the framework of action control intended to explain the control of self-performed actions can be successfully applied to external actions or cause-effect relationships.

ERRONEOUS INTERNAL CAUSATION: IDEOMOTOR PHENOMENA

There is a class of phenomena that show a close link between action control and visual causality, involving movements that are erroneously attributed to the observer: Ideomotor phenomena (Carpenter, 1874, p. 286) may be observed when people observe other people (or objects) doing something. A typical example would be watching sports on television. A large number of people, although quietly sitting in their armchairs, cannot help but tense their muscles, shift their bodies to the left and right, or twitch their legs (when watching a soccer game). None of these movements are instrumental, that is, whatever the observer is doing, it does not influence the course of the game on television. Despite the evident uselessness of this type of behavior, observers cannot refrain from carrying it out. What observers see somehow induces a tendency to move. Two potential mechanisms may explain this odd behavior. First, it may be possible that observers have a very simple tendency to imitate what they perceive. Second, observers may try to achieve particular effects (of course these attempts are in vain), for instance guiding the football into the goal, or deflecting it away from the goal (depending on which team has the observer's sympathies). These two forms of induction may be referred to as perceptual and intentional induction (Knuf, Aschersleben, & Prinz, 2000). Knuf et al. investigated the two forms of induction in a billiard-like setup. The task was to steer a ball by means of a joystick such that it would hit a second ball, the goal. However, after a brief instrumental phase during which subjects actually controlled the ball's trajectory, they lost control of the ball. This was well-known to the subject. However, unbeknown to the subject, the joystick coordinates were recorded in the non-instrumental phase (after control was lost). Although all movements in this phase were non-instrumental, subjects did move their hands. An analysis of these ideomotor actions showed that subjects tried to guide the ball into a particular direction. To this end, they performed a movement that was opposed to what they saw. This leads to the conclusion that the observed movement produced some form of intentional induction. Subjects showed a tendency to execute movements that would achieve a particular effect in the object they previously controlled, but they did not imitate the movement of the object. A similar observation can be made in almost any soccer game: Whenever the ball appears to miss the goal to the left, observers tilt towards the right as if attempting to guide the ball into the goal. This illusion of internal control points to the importance of action effects for action control, and also shows that the boundaries between actions and their effects are less clear-cut than one may suspect. Remember that a similar pattern was observed for externally controlled actions: The actor was perceived to have control (and to accelerate) the ball even after the ball had left the hand. Similarly, ideomotor actions were performed after control had ceased.

The important role of intentions in the perception of action effects prompts us to speculate that the underlying concept of causation in ideomotor phenomena (Knuf et al., 2000), and judgements of velocity profiles (Hecht & Bertamini, 2000), is akin to a causa finalis and not to the causa efficiens mentioned in the above. According to this notion, intentions directly cause movements: Our will to throw the ball explains its flight. Thus, one may reinterpret the errors committed by our perceptual system as the dominance of the causa finalis over the causa efficiens. Similarly, our will to guide the ball governs our non-instrumental movements. The flight of the ball is ascribed to the (unfortunately vain) intention to propel it.

The prominent role of intentions and action effects in perception is not accidental. One very important role of perception is the recognition of social factors (discrimination of aggression or flight, fast evaluation of the intention of approaching objects, etc.), such that a confusion of properties of inanimate objects (causation) and animate subjects (purpose or intention) seems inevitable (see Gelman, Durgin & Kaufman, 1995).

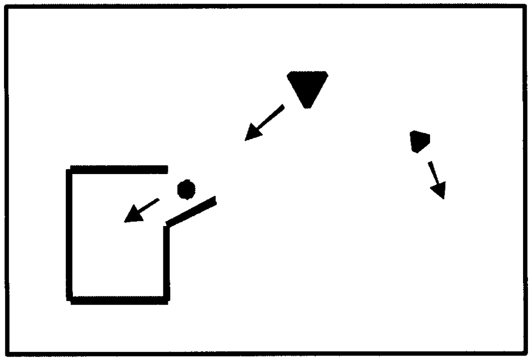

Figure 6. Geometric figures that were used by Heider and Simmel in a cartoon. Movements of the figures are seen as actions and the figures take on particular traits.

This assumption may explain why we spontaneously see intentions, emotions, and social relationships in simple movements of geometrical objects (Heider & Simmel, 1944). When the geometric drawings in Figure 6 are animated, as indicated by the arrows, observers agree on a description in which the large triangle is a villain chasing the circle. The small triangle is the friend of the circle (apparently a female), and the large rectangle is a house. Already infants tend to interpret simple movements as intentional (e. g. Corrigan & Denton, 1996; Premack & Premack, 1997) and even static objects may be interpreted in a causal manner that takes into account the history of the object's deformations (Leyton, 1992). For instance, a bent object reveals the past effect of impact.

PERCEIVED CAUSALITY IN ARTIFICIAL SYSTEMS

Now, let us apply to modern tools what we know about visual causality in situations that provoke misjudgments. Actions in artificial systems, for instance in the fly-by-wire control of an airplane or in television-supervised surgery, involve an artificial separation of our perception from our effectors (hands). From an evolutionary perspective, the perception of causality has been intimately tied to our effectors: we were able to see the effects of our motor actions in a direct and unmediated way (grasping, throwing, beating, etc.). Complex tools add a layer of mediation or a gap between motor command and effector. This gap is predestined to exacerbate the confounding of actual causes with intentional factors and constraints of the human motor system. For example, in the mediation of a TV-monitor, a surgeon's executed incision may look better than it is because it was intended that way. The reduced visual resolution of the image on the monitor may prevent the correction of the sloppy incision. That is, in situations where feedback about the true effect of our actions is delayed or imprecise, the causa finalis may stand uncorrected. Needless to say, serious mistakes can result.

Our hypothesis is that the width of the gap between our hands and the artificial effectors is directly correlated with the degree to which our actions are contaminated with erroneously perceived causes. The contamination of our perception by the causa finalis, suppressing veridical perception of the causa efficiens, is also hypothesized to grow with the degree to which the artificial system becomes cognitively less penetrable. Within an ill-understood system, the contamination is less likely to be detected and corrected. In order to avoid illusory control, the limits of causality perception, as well as the intentions of the perceiver have to be taken into consideration

From a perceptual perspective, the understanding of the nature of causal contamination is required in order to successfully build systems that prevent such effects. Visualizations in artificial systems have to respect the natural limits of our perception of causality. Results from research on the perception of mechanical causality show that the experience of causality is only possible within certain spatio-temporal limits. Slow transfer rates, or low spatial resolution of the displays in virtual realities prevent the impression of causality. If these technical limitations cannot be overcome, it remains doubtful as to whether users of such systems will be able to perceive the effects of their own actions adequately. Moreover, artificial displays must be designed that modify the visual rendition of effects such that they accentuate the dividing-line between true and illusory control. Thus, the understanding of visual causation is indispensable in the context of artificial systems.

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