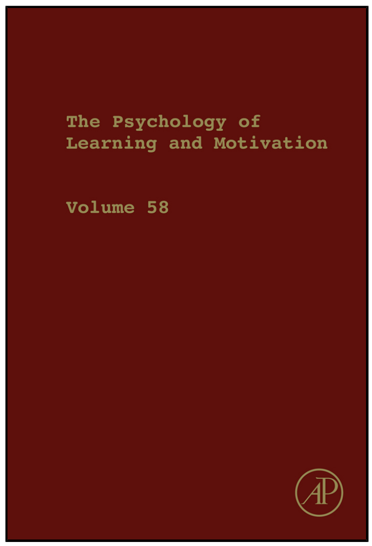

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CHAPTER FIVE

Causation, Touch, and the Perception of Force

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Contents

Abstract

Much of the thinking on causation recognizes that it entails more than spatial–temporal contiguity or correlation, but it has been difficult to specify exactly what that extra component of thought is. In this paper, we argue that the representation of causal relations is based on the feeling of force as understood through the sense of touch. Grounding causation in people's sense of touch allows us to address the long-standing challenges that have been raised against force-based approaches to causation.

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In support of our proposal, we review research on the perception of causation that provides support for a force-based view of causation. We also describe recent findings that establish a direct connection between people's impressions of causation and their sense of touch. We conclude by showing how a force-based view can be extended to handle the problem of how abstract causal relations are represented and acquired.

1. INTRODUCTION

Headlines in the popular press sometimes report correlations in a way that strongly suggests a causal relationship, such as "Eating Pizza Cuts Cancer Risk"[1] or "Eating fish prevents crime"[2]. Such misrepresentations occur, no doubt, because causal claims indicate something deeper and more significant than correlational claims, but also because the exact nature of the difference between the two kinds of claims can be difficult to specify, thus affording a certain amount of wiggle room for artistic license.

In this article, we offer an account of how causation differs from correlation. In particular, we defend the thesis that the conditions that license causal attributions are not based on simple outward appearances, such as sequences of events occurring closely in space and time, but rather are based on the feeling of force as understood through the sense of touch. Thus, causal impressions are held to be grounded on more than the *kinematic* properties of an event—the entities, their motions, points of contact, and property changes—but rather on the perceived *dynamics* of an event, the forces and energies that bring about changes. As discussed below, the view that the sense of causation is based on force is arguably the first theory of causation put forth in recorded history, as well as the one that has been most heavily criticized. In offering a defense of forces, we will address some of the criticisms that have been raised, including the issues of the meaningfulness of forces and how forces might be acquired from experience. Our response to these criticisms will rest on the proposal that people understand forces as somatosensory impressions, i.e. in terms of their senses of touch, proprioception, and balance.

We begin by offering an account of how causation might be defined in terms of forces and then explain how this account fits within the history of proposals on causation. One of the themes that will emerge from this review is the issue of how causal relations might be acquired from

[1]BBC News, July 22, 2003, Retrieved from http://jfmueller.faculty.noctrl.edu/100/correlation_or_causation.htm.

[2]The Observer, September, 14, 2003, Retrieved from http://jfmueller.faculty.noctrl.edu/100/correlation_or_causation.htm.

experience. With respect to force-based theories, the issue centers on how people infer forces from the environment. As we will see, numerous studies have examined the encoding and storage of forces in the environment. After addressing the topic of acquisition, we focus on what prior research says about the representation of causation in terms of forces. Our search will include a close examination of the research on the perception of causation from collision events. With this background established, we describe recent findings that provide direct evidence for the proposal that casual relations are understood in terms of force, with force defined in terms of the sense of touch. We end with a discussion of how a force-based approach might account for the representation of abstract causal relations. In explaining the origins of causation, we arrive at an answer to the question of exactly how causation is more than mere correlation.

2. FORCE-BASED ACCOUNTS OF CAUSATION

In prior work, we have shown that causal relations can be understood in terms of configurations of forces (Wolff, 2007; Wolff & Song, 2003; Wolff, Barbey, & Hausknecht, 2010; Wolff & Zettergren, 2002). I refer to this account, which is based on Talmy's (1988) theory of force dynamics, as the dynamics model. According to the dynamics model, individual causal relations involve two main entities: an affector and a patient (the entity acted on by the affector). The theory holds that people specify causal relations in terms of configurations of forces acting on the patient. One of the forces acting on the patient is the force imparted on the patient by the affector. Another force is the force generated by the patient itself, or the patient's tendency to resist moving in a particular direction. The two forces can be added together to form a resultant force, which is then compared against an endstate vector in order to establish the patient's change in direction. The predictions of the theory have been tested in several studies (Wolff, 2007; Wolff & Song, 2003; Wolff et al., 2010). For current purposes, the main point is that this recent account of causation can be traced back almost 2500 years.

2.1. Aristotle's Force-based Approach to Causation

The idea that the concept of causation is based on force has its origins in ancient Greek philosophy. An initial first step was the atomistic influx model of Democritus (460–370 BC), which held that causation was produced by the transmission of an agent's substance—in the form of atoms—to the patient (O'Neill, 1993). The atomistic influx model, in turn, appears to have influenced Aristotle's (384–322 BC) causal powers approach to causation. According to Aristotle, causation involves the transmission of a "form" from the agent to the patient (Marmodoro, 2007; Witt, 2008). For example, in a situation where a fire acts on a pot, the transmitted form would be heat. Aristotle emphasized that in a causal interaction, both the agent and patient have causal powers: the agent, the ability to transmit a form, and the patient, the capacity to receive the change. It is interesting to note that throughout Greek scientific literature, the word for power (and sometimes force) was *dynamis* (Jammer, 1957), which eventually gave rise to the modern day word *dynamics*, the branch of mechanics that deals with forces and their relation to motion. In Greek, *dynamis* meant "strength" or "power", but also "ability" or "faculty" (Witt, 2008). Aristotle differentiated two types of causal powers: active and inactive. Inactive powers were understood as tendencies or potentialities for some kind of actuality[3]. As described below, this aspect of Aristotle's theory of causal power was carried over into his thinking about forces.

In addition to a causal powers theory of causation, Aristotle was one of the first philosophers to make an explicit link between causation and force (Jammer, 1957). It has been stated that Aristotle viewed forces as a particular type of cause (Heidegger, 1995), namely, the type associated with physical pushes and pulls (Jammer, 1957). Evidence for this view can be found in many places, including multiple references to forces being causes in Aristotle's eighth book of his Physics (1999):

> *Of intrinsic motions, some are caused by the thing itself, some by another thing, and some happen by nature, and others happen by force and contrary to nature. (p. 9)*

In "The Eudemian Ethics", we see that Aristotle also saw forces as causally relevant to the actions of living things and that he viewed them much like causal powers since they interacted with tendencies (2011):

> *Similarly, with living things, including animals, we see them being acted on by force, and also acting under force, when their motion is caused by an external agent against their intrinsic tendency. (p. 27)*

Indeed, Aristotle (2011) plainly states that forces can serve as psychological causes in a manner analogous to physical forces.

[3]Talmy's (1988) theory of force dynamics shares a number of features with Aristotle's theory of causal powers, in particular, the notion that both the agent and patient have intrinsic tendencies and play a role in a causal interaction.

It has already been said that these people seem, exceptionally, to act both voluntarily and by force, the reason being a certain similarity to the kind of force that we speak of also in connection with inanimate things. (p. 28)

2.2. Criticisms of Aristotle's Force-based Approach to Causation

Aristotle's ideas about causation dominated thinking on the topic for the next 2000 years. However, during the fifteenth and sixteenth centuries, it came under wide criticism. A quick review of these criticisms is worthwhile because some of the same arguments are still put forth today (e.g. Cheng, 1997; Cheng & Novick, 1991, 1992; Schulz, Kushnir, & Gopnik, 2007; Woodward, 2007).

For philosophers in the fifteenth and sixteenth centuries, Aristotle's account of causation fell short because the notion of force was too mysterious to be useful. To understand this perspective, it needs to be recognized that during this time, many philosophers were attracted to the idea of natural mechanism, that is, the view that living and other natural things behaved the way they did because they were like machines (Ott, 2009). As machines, their behavior could be explained in terms of their mechanical properties, that is, in terms of local interactions of parts, just as the behavior of a clock could be explained in terms of the size, shape, position, and movement of its gears. The Aristotelian view of causal powers and forces conflicted with the mechanistic view because it was unclear how these notions could be defined in mechanistic terms. For example, it was unclear how defining gravity as a force improved our understanding of gravity, unless the notion of force could be grounded in terms of local interactions of parts. Explanations based on causal powers or forces were viewed as little more than appeals to the occult.

Some modern philosophers, such as John Locke (1632–1704) and Robert Boyle (1627–1691), tried to combine Aristotelian ideas with mechanistic thinking (Ott, 2009). Others, including René Descartes (1596–1650), Nicolas Melebranche (1638–1715), and David Hume (1711–1776), ruled out the possibility of causation in terms of powers or forces altogether. For Hume (1748/1975) in particular, the problem with force was that it could not be linked to any internal or external sensory impressions. Hume (1748/1975) acknowledged that after many repetitions of conjunctions of objects or events, people would develop an expectation that could be interpreted as a power or force, but this power or force could not serve as the basis of causation because it resulted from thoughts projected onto experience rather than from experience projected onto thought.

Newton's (1643–1727) theory of force gave modern philosophers pause (Jammer, 1957). On his account, the notions of causation and force were connected. In his General Scholium, Newton wrote that causes were forces that changed the course of events, specifically, "The causes by which true and relative motions are distinguished, one from the other, are the forces impressed upon bodies to generate motion" (Newton, 1687, I: 14). Newton inspired other force-based theories, including those developed by Martin Knutzen (1713–1751) and Immanuel Kant (1724–1804). What Newton's theory suggested was that forces might be instantiated independently of the mind, which must hold if they are to serve as the basis of causation. At issue, then, is whether they could be perceived directly. According to Hume (1748/1975), they could not because they left no impression on the senses.

2.3. Grounded Force-based Approaches to Causation

Several proposals have challenged Hume's claim that forces cannot be sensed, the common thesis being that forces can be sensed if they are linked to our will or haptic sense. This idea was first proposed by Thomas Reid (1710–1795), who suggested that the ideas of force, power, and causation were derived from our conscious awareness of voluntary actions. According to Reid, "It is very probable that the very conception or idea of active power and of efficient causes is derived from our voluntary exertions in producing effects…" (Reid, 1788/2010, p. 250; see also Jammer, 1957). A similar view was offered by Maine de Biran (1766–1824), who, like Reid, argued that the prototype for our idea of force is found in our own will (Jammer, 1957; Piaget, 1930/1969; Truman, 1904). For de Biran, the concept of cause is based on the inner consciousness of force that stimulates a voluntary bodily motion or mental process as well as the kinesthetic sensations that accompany muscular contraction. Piaget (1930/1969) held the related belief that forces consisted of schemas built up from muscle experiences and the accompanying sense of effort. Piaget viewed his theory as partially consistent with de Biran's in that they both viewed force as having an internal origin that could later be attributed to things in the external world.

In the current literature, an account related to all of these hypotheses has been proposed by White (1999, 2006, 2009, 2012a, 2012b). According to White (1999, 2006), the idea of causation originates from actions on objects. Such actions provide two kinds of input. The first is the experience of motor activity; the other is the haptic sensations produced by pressure sensors in the skin and sensation from bodily position, weight, muscle tension and movement (i.e. kinaesthesis). White emphasizes that both motor activity and haptic sensation are required to establish knowledge of causation. White further argues that actions on objects lead to the formation of schemas specifying forces. These schemas are important because when people see patterns of motion, these patterns are matched to the schemas of force stored earlier. Thus, it is people's direct experiences acting on objects that allow them to infer forces in events perceived visually (White, 2012a; see also Piaget, 1930/1969). In more recent work, White (2011, 2012a) concludes that the perception of causation is not directly based on the perception of forces, though he still holds that the perception of forces is based on people's experiences acting on objects and that collision events give rise to the perception of force.

In all of the proposals discussed so far concerning how forces may be grounded in the body, the idea has been that when we perceive forces in the world, we adopt the role of agent over the role of patient. In other words, we apply our own personal experiences to entities in the external world from the point of view of the active entity rather than the inactive one (White, 2006, 2012a). A recent proposal by Fales (1990) adopts the alternative possibility. As in the other proposals, Fales (1990) argues that causation is based on force and that our notions of force have a sensory basis. Fales (1990), however, emphasizes that our notions of force are based primarily on experiences in which our bodies are acted on by other entities. In particular, he highlights the role of the tactile perceptions that accompany impingement upon our bodies as well as our kinesthetic sense and our sense of balance (1990). Our kinesthetic sense records sensations associated with the relative motion between different parts of our bodies produced by the extension of skeletal muscles. Our sense of balance depends on the vestibular apparatus in the inner ear and is designed to sense generalized forces such as gravity and centrifugal forces. Fales (1990) points out that our tactile and kinesthetic senses may be sensitive to different forces, or to the same force. Importantly, the sense of force experienced through these different senses can be integrated using vector algebra to compute resultant forces specifying magnitude, direction, and point of application. As we will discuss below, recent experiments support Fales' (1990) patient-oriented theory over White's (1999, 2006, 2012a), Reid's (1788/2010), Maine de Biran's (Jammer, 1957; Piaget, 1930/1969; Truman, 1904) and Piaget's (1930/1969) agent-oriented theories.

Recent years have witnessed a resurgence of interest in the idea that causation might be based on causal powers (Ahn & Bailenson, 1996; Ahn, Kalish, Medin, & Gelman, 1995; Aronson, 1971; Bullock, Gelman, & Baillargeon, 1982; Dowe, 2001; Fair, 1979; Harre & Madden, 1975; Salmon, 1994, 1998; Shultz, 1982). This renewed interest has resulted in demonstrations of how force-based representations allow us to differentiate causation from noncausation and various other types of causal categories (Ahn & Kalish, 2000; Bigelow et al., Bigelow & Pargetter, 1990; Leslie, 1994; Strawson, 1987; Talmy, 1988; Wolff, 2007; Wolff & Zettergren, 2002). Nevertheless, the notion that forces play a role in causal understanding continues to attract significant opposition. Arguably, the strongest criticism against force-based accounts is that originally raised by Hume (1748/1975), namely, that the notion of force cannot provide a basis for causation because it cannot be sensed. Recent research indicates that Hume overstated his case. While it is true that forces are invisible, vision is not our only sensory modality. Once we consider the potential contributions of the other senses, most notably touch, it becomes clear that people's sensory experiences are not as deficient as Hume claimed.

3. GROUNDING FORCES IN THE SENSE OF TOUCH

The brain, in fact, devotes a fairly large amount of real estate to the processing of forces. The system responsible for determining whether forces have been applied against the body is the somatosensory system. Anatomically, the system is divided into two parts. The postcentral gyrus (or anterior parietal cortex), which consists of Broadmann areas 3, 1, and 2, is the location of the primary somatosensory cortex (SI) and the parietal operculum (the upper bank of the lateral sulcus) is the location of the secondary somatosensory cortex (SII) (Keysers, Kaas, & Gazzola, 2010). Both cortices process touch and proprioception. Touch is the sense by which pressure exerted on the skin is perceived, pressure being a function of force, namely, force divided by surface area. Proprioception (or kinesthesia) is the sense though which we perceive the position and movement of our body, including our sense of equilibrium and balance, senses that depend on the notion of force (Jones, 2000).

3.1. Evidence for the Representation of Forces from Psychophysics

There is much evidence that the somatosensory system, in particular the tactile system, is fairly adept at distinguishing force magnitudes. This finding emerged, for example, in a study by Wheat, Salo, and Goodwin (2004), in which participants estimated the magnitudes of forces applied to their index fingers. The researchers observed a nearly linear relationship between participants' estimates and the actual magnitude of the force acting on their fingers (see also Jones & Piateski, 2006). Related research has shown that people are able to distinguish force directions. For example, Panarese and Edin (2011) asked participants to discriminate the directions of forces applied to the index finger and found that they were able to discriminate forces that differed by only 7.1°.

Beyond basic discrimination, abundant evidence indicates that people store information about forces. Indeed, the storage of forces is revealed in common everyday tasks. Many of us, for example, have had the experience of reaching for a suitcase or box and over-lifting it because we thought it was full when, in fact, it was empty (Reinkensmeyer, Emken, & Crammer, 2004). Such events suggest that we estimated the weight of the suitcase, a type of force, before we lifted it, and because we estimated wrongly, we generated greater-than-necessary forces. Experimental evidence for the storage of forces comes from studies that put people in "force fields" and then observe their subsequent motor actions. For example, in a classic study by Shadmehr and Mussa-Ivaldi (1994), participants were instructed to move their hand from one point to another while holding onto a robotic arm (i.e. a manipulandrum). The robotic arm was programmed to generate forces that pushed the person's hand away from the target location. With repeated practice, people learned how to overcome the pressure of the robotic arm and to reach straight for the intended target. The key finding was the appearance of an aftereffect once the force field (robotic arm) was removed: people's arm trajectories were distorted in the opposite direction of the previously applied force. The result implies that people had internalized the force field. Similar findings have been observed in conditions of microgravity, that is, when people are placed into the weightless condition of parabolic flight and asked to reach for certain targets (Papaxanthis, Pozzo, & McIntyre, 2005). Changes in the trajectories of their arms imply that people factor into their motor plans the forces of gravity and inertia. Another type of experiment examining lifting behavior has revealed evidence for the role of forces in people's motor actions. For example, it has been be found that people generate larger gripping and lifting forces when they pick up larger objects than smaller objects (Gordon, Forssberg, Johansson, & Westling, 1991). Additional research on lifting shows that people can store information about more than one force and then combine these forces. In a fascinating study by Davidson and Wolpert (2004), people learned the forces needed to lift two objects independently. The two objects were then stacked together. Pressure sensors on the objects showed that the amount of pressure they applied to the stack of objects was a weighted sum of the pressures they had applied to the objects when they were lifted independently.

Evidence for the representation of forces in these motor planning studies has been attributed to the formation of an internal model that represents the dynamic properties of the environment (see also Conditt, Gandolfo, & Mussa-Ivaldi, 1997; Hinder & Milner, 2003; Imamizu, Uno, & Kawato, 1995; Kawato, 1999; Milner & Franklin, 2005; Ohta & Laboissière, 2006).

3.2. Evidence for the Representation of Forces from Weight Illusions

Research examining people's judgments of weight have found that inferences about forces are based on several kinds of cues. For example, Hamilton, Joyce, Flanagan, Frith, and Wopert (2007) observed that people used the fine details of a lifter's kinematics in their estimates of weight. In their study, participants watched videos of a person picking up boxes of different weight and then estimated the weight of a box on a 1 to 100 scale. Participants' weight estimates were found to be a function of the duration of the lift phase, transportation phase, and grasp phase (see also Shim & Carlton, 1997). Other cues people used to judge an object's weight were its size and density. They tended to assume that large and dense objects weighed more than small and airy objects (Walker, Francis, & Walker, 2010). Research on various types of weight illusions tell us that these cues are used spontaneously in people's estimations of weight. For example, in the size–weight illusion, when people are asked to estimate the relative weight of a large object and a small object that in fact weigh the same, they will mistakenly perceive the smaller object as weighing more than the larger object (Flanagan & Beltzner, 2000; Kawai, Henigman, MacKenzi, Kuang, & Faust, 2007). The phenomenon is typically explained as resulting from a mismatch between expectations and actual sensory experience. People expect the small object will weigh less than the large object, but when they learn this isn't the case, they mistakenly over-estimate the weight of the smaller object. In a related illusion, the weight of objects made of low-density materials (e.g. Styrofoam) are perceived to weigh more than those made dense materials (steel) even though their actual weights are exactly the same (Ellis & Lederman, 1999). The key point for our purposes is that the perceptual–conceptual system spontaneously estimates forces on the basis of cues such as size and material.

3.3. Evidence for the Representation of Forces from Neural Imaging

In all of the research on people's ability to represent force discussed so far, participants were asked to either perform a motor action or provide a judgment. One question left open by this research is whether people make spontaneous inferences about forces even when an explicit action or judgment is not required. Recent work using neural imaging suggests that they do. The surprising finding from this research is that the somatosensory cortices become active not only when a person is touched but also when they observe touching. In a study by Keysers et al. (2004), participants were either touched on their legs or viewed movies of other people or objects being touched. They found that the SII was activated in all conditions. In particular, activity in SII was observed both when the person was directly touched on the leg as well as when they saw another person being touched on the leg. Moreover, when the legs in the video were replaced by paper towels, activity in SII was still observed when there was touching, suggesting that the activity in SII corresponds to a relatively abstract notion of touching. Interestingly, in the observation conditions, Keysers et al. did not find activity in SI. As noted by Keysers et al., the finding of activity in SII is consistent with recent interpretations of SII as a site of integration between somatosensory information and information from other senses, like vision.

Keysers et al.'s (2004) findings have been replicated and extended in several other studies. For example, Blakemore, Bristow, Bird, Frith, and Ward (2005) found that observing another person touch his or her face resulted in activity in the face region of the viewer's SI. Ebisch et al. (2008) presented participants with videos showing intentional and accidental touching occurring between animate and inanimate objects. The videos involved scenes in which a person touched another person or a chair, or a branch touched a person or a chair. As with Keysers et al. (2004), Ebisch et al. (2008) found activity in SII for all conditions. Interestingly, they found some activity in SI/BA 2 for the videos depicting intentional touching (i.e. the videos in which the agent was a person). In a studying using magnetoencephalography, Pihko, Nangini, Jousmäki, and Hari (2010) obtained a similar pattern of findings. The participant's hand was touched by the experimenter or the participant observed the experimenter touch her own hand. As in previous studies, the somatosensory cortex was activated in both the directly experienced and observed conditions. However, unlike in previous studies, Pihko et al. (2010) observed activity in the SI only. Also, interestingly, Pihko observed that the activity in the observed condition was 7.5% of the activation in the directly experienced condition. Finally, Meyer, Kaplan, Essex, Damasio, and Damasio (2011) pursued a very different approach to the question of whether touch activates the somatosensory cortex by probing the informational content of the activity in that region. Participants watched people handle various everyday objects. As in previous studies, it was found that watching touching resulted in activity in the somatosensory cortex, specifically SI. Especially impressive, using multivariate pattern analysis, Meyer et al. (2011) were able to predict which of the several objects was being handled based exclusively on the pattern of activity in SI.

One question these studies did not address concerns how the link between vision and touch is formed. One possibility is that the association is built into the architecture from birth. Alternatively, as proposed by Keysers et al. (2004), it may result from ordinary associative learning. When people see themselves being touched, this visual sensation will overlap with the somatosensory sensation of being touched. With repetition, this association will be built up so that people experience a somatosensory sensation of being touched in response to a visual stimulus of touching, even in the absence of actual physical touch.

Under the assumption that forces are processed, at least in part, in the somatosensory cortex, the studies reviewed above offer strong evidence that people are able to represent forces and that they spontaneously engage in the encoding of forces from visual information. Thus, in contrast to the claims of Hume, people's sensory experiences do appear to include forces.

4. EVIDENCE FOR A FORCE-BASED VIEW OF CAUSATION FROM WORK ON THE PERCEPTION OF CAUSATION

The previous section established that people automatically infer and store forces from the environment, but such abilities do not necessarily imply that their notion of causation is based on forces, just that it *could* be based on forces. In the following sections, we examine the evidence in support of a force-based view of causation. We begin by examining the extent to which past research offers evidence in support of the view that people's representations of causal relations are based on forces. In particular, to what extent does the launching event give rise to the perception of forces, which in turn leads to a causal impression?

Michotte (1946/1963) provides a mostly contradictory answer to this question. The bulk of his work emphasizes the importance of kinematics over dynamics. This emphasis comes through especially strongly in experiments looking at "paradoxical cases", situations in which the essential conditions for the causal impression are fulfilled but in such a way that the stimulus properties of the event conflict with everyday experience and the laws of mechanics. Michotte cited such cases to argue that the stimulus properties that give rise to the causal impression must be innate because they could not be learned from experience. In fact, a close examination of such cases (see below) shows that they are not so much at odds with the laws of mechanics as Michotte claimed. Moreover, if we consider the more typical cases giving rise to the causal impression, we see that they appear to provide strong support for the claim that the causal impression is based on forces because the stimulus characteristics of these events are exactly those of events in which forces are produced. Indeed, in the conclusion of his book, Michotte seems to change stories rapidly when he asserts "the causal impression is *the perception of the work of a mechanical force*" (p. 228). Interestingly, there is a way in which the two parts of Michotte's story can be unified. As noted in the previous section, certain stimulus properties, such as size and material, can serve as cues to force. Such cues are not infallible, just relatively reliable indicators of force. Similarly, the stimulus conditions identified by Michotte may serve as cues to force rather than as direct triggers of the concept of cause. A review of some of Michotte's paradoxical cases will offer support for such an account.

4.1. Michotte's Arguments against Force-based Accounts

One reason why Michotte felt that the causal impression was based on a particular stimulus pattern and not the laws of mechanics was that people sometimes reported perceiving causation in events that he viewed as physically impossible. For example, people reported perceiving causation in situations in which objects A and B were moving in the same direction, A faster than object B, and after A hits B, A stopped and B slowed down (Michotte, 1946/1963, p. 71). On the basis of such results, Michotte concluded that the causal impression was not based on past experience with the world, which of course, honors dynamics: had people referred to past experience, they would have expected object B to speed up, not slow down, after being hit. However, while such the experimental sequence of events may be unusual, it is not necessarily at odds with a force-based account of causation. Friction can change dramatically over the course of an object's movement, as when a ball rolls off an asphalt road and onto a gravel driveway. Michotte's "impossible" event is not, in fact, impossible in the world, and so his finding does not necessarily rule out the role of forces in the perception of causation.

Another of Michotte's arguments for the independence of the launching effect and the laws of mechanics is that sometimes the causal impression failed to obtain for trajectories that people experience in the real world. In support of this point, Michotte conducted several Experiments (34 and 35) in which object A hits object B directly and B traveled at an angle away from its expected straight-line path. The degree of deviation from B's expected straight path ranged from 25 to 90°; as the size of the angle increased, the causal impression grew weaker. Recent studies (Straube & Chatterjee, 2010; White, 2012b) have replicated this finding. Michotte points out that this result is at variance with our real-world experience in which two colliding objects can travel at angles (beside 180°) and still be viewed as causal (e.g. billiards, marbles). However, Michotte's collision events were quite different from those involving billiard balls and marbles. As noted by White (2012b), in the real world, B's direction of movement depends not just on the direction of A, but also on where B is hit, that is, on its point of contact. If an object is hit from below its center of mass, a force view predicts that the object will move upwards, in a direction that differs from A's, not straight ahead. In Michotte's experiments, A hits B head on, and so a force-view would predict that B's direction should be straight ahead, but what people saw was B moving away at an angle. Given that such direction is at variance with the forces involved in the situation, it is not surprising that people's causal impressions decreased as the angle of departure increased. Indeed, in an experiment reported in White (2012b), people's causal impressions were high for events involving angles, so long as the direction conformed to the direction that would be expected from A's direction and A's and B's point of contact. As White (2012b) notes, this result contradicts Michotte's hypothesis that the causal impression depends on continuity of motion between A and B, and instead supports the view that the causal impression depends on people's real world experiences with collision events.

A third argument raised by Michotte that the causal impression was not tied to the laws of mechanics is that people experience the causal impression even when the objects involved are spots of light, shadows, or lines painted on a rotated disk. In other words, people perceive causation while also knowing that such causation does not occur in the real world (1946/1963, pp. 84–85). However, a force-based approach to causation does not imply that people cannot be subject to illusions of causation. A particular configuration of forces will produce only one kinematic pattern, but a single kinematic pattern is potentially consistent with more than one configuration of forces. This asymmetry explains why causal illusions can sometimes occur: people may infer the wrong configuration of forces from a particular kinematic pattern. This is especially likely when the actual forces driving the kinematics are obscured, as in the case of Michotte's launching events. Further, the process of inducing forces is likely to be at least partially automatic (Runeson & Frykholm, 1983), so causal illusions may occur even when the inferred configuration of forces is inconsistent with prior knowledge of the situation.

It should also be noted that while Michotte claimed that the launching event was largely independent of the shape and size of the objects involved in the event, more recent research indicates that object properties do, in fact, influence the perception of causation (for a review see Saxe & Carey, 2006). A convincing example of the importance of object properties on the impression of causation was demonstrated in a study by Kotovsky and Baillargeon (1998), in which 5.5- and 6.5-month-old infants were shown an event in which a cylinder rolled down a hill and hit a "bug", after which the bug moved to the center of the stage. Once the infants were habituated to this event, they were shown the same event again, except that the cylinder was replaced with either a smaller or a larger cylinder, and the bug moved further across the stage. One of the key findings was that the 6.5-month-olds looked longer at the trials involving the small cylinder than at those with the large cylinder, suggesting that they were surprised to see a larger effect follow from a smaller causal object. This result makes sense if infants' causal impressions are based, at least in part, on forces: smaller objects cause smaller forces and hence, smaller effects; any other pattern is viewed as surprising.

4.2. How Michotte's Findings Indicate the Role of Forces in the Perception of Causation

Michotte emphasized that the causal impression was not a mere copy or reproduction of what goes on in the real world, but the main findings of his research program indicate just the opposite. For example, Michotte observed that the causal impression disappeared when there was a temporal delay of around 150 ms between the moment objects A and B made contact and the moment B began to move. This finding is easily explained by a force-based account of causation. When object A hits object B, the force imparted on B is instantaneous. If object B begins moving well after it is hit, its movement cannot be due to the force imparted by object A. The importance of temporal contiguity in the perception of cause has been replicated in a number of studies (Morris & Peng, 1994; Oakes & Kannass, 1999; Schlottmann & Anderson, 1993; Schlottmann & Shanks, 1992; White, 2010). Another finding of Michotte's is that the perception of causation is strongest when object A makes physical contact with object B. This finding is also consistent with a force-based approach, since contact forces cannot exist unless objects make contact with one another. The effect of physical contact on the causal impression has also been demonstrated in a several studies (Kotovsky & Baillargeon, 2000; Schlottmann, Ray, Mitchell, & Demetriou, 2006; Spelke, Phillips, & Woodward, 1995).

Another phenomenon associated with the causal impression is the *radii of action*. The radii of action are the portions of the paths traveled by A and B that appear to be relevant to the impression of causation. When B travels beyond A's radius of action, it appears to be moving on its own, not as a consequence of the collision. Michotte found that object B's radius of action increased with the speed of object A. Michotte was unable to offer an explanation for the phenomenon because whether B remained within the radius of action or traveled beyond it had no consequence for event's continuity of motion, the hypothesized source of the causal impression. In contrast, force-based approaches to causation offer a natural explanation: as object A's speed increases, the force it imparts on B increases, and, in turn, so does the distance B travels as a consequence of A's impact (for a related proposal, see Hubbard & Rupel, 2002).

Finally, as noted above, according to Michotte, the causal impression should be strongest when the two parts of a launching event constitute a single continuous movement, whereby the motion of the first object extends into the second and creates an "ampliation of motion." According to this hypothesis, any differences in velocity between the first and second objects should decrease the causal impression, because any difference in velocity makes the sequence of events less continuous. However, in contrast to this prediction, Michotte found that the causal impression was stronger when the speed of object B was slower than that of object A. Specifically, in Experiments 15 and 39, people reported a much stronger causal impression when the ratio in speed of objects A and B was 4:1 than when the ratio was 1:1. This result is consistent with a force-based approach to causation. The reason why the second object moves less rapidly than the first is because at the point of contact there is loss of energy. Moreover, under the assumption that B's movement is due to external forces, B should ultimately slow down as it is acted on by friction with the surface. When object B's speed is the same as object A's, force-based accounts predict that the causal impression should be weaker because it suggests that some other forces must be involved in the production of B's movement.

In sum, research on the launching event supports the thesis that the notion of causation is ultimately based not on outward appearances, but rather on the notion of force. Once we conceptualize causation in terms of force, we are able to explain why the perception of causation depends on spatial and temporal contiguity in the launching event. We are also able to explain why the perception of causation is affected by differences in the speed of the two objects. In sum, a force-based approach allows us to make better sense of the phenomena surrounding the launch event. That said, the current literature does not offer the kind of evidence needed to make the claim that causal relations are associated with the representation of forces. The research described in the next section takes an initial step toward filling this gap.

5. THE SENSE OF FORCE IN CAUSAL PERCEPTION AND INDUCTION

The proposal that causation is based on force has implications for the perception of causation. The proposal implies that when people see causal events, they should simultaneously infer forces. In the experiments described below, we tested this possibility (Wolff, Ritter, & Holmes, in preparation) by examining whether "seeing a force" had an effect on "feeling a force." In order to test this prediction, we needed to be able to impart precisely timed forces and measure people's reaction times to these forces. This was accomplished using a haptic controller device. A haptic control is essentially a small robotic arm. Like a mouse, you can push it around, but unlike a mouse, it can push back. The arm has impressive capabilities. It can be used to "feel" virtual surfaces that are bumpy, sticky, smooth or rough. For the purposes of the following experiments, we needed the arm to do one simple thing: impart a force at an exact point in time against people's hands. The controller had a small button that people could press to indicate that they experienced a force. The controller was programmed using widely available C++ libraries.

5.1. Forces in the Perception of Direct, Physical Causation

In the first three experiments, we focused on events involving physical forces. As described in greater detail below, each experiment included three conditions, which were run between participants with 25 participants in each condition, for a total of 75 participants in each experiment. Frames from the animations used in these experiments are shown in the first three pictures of Figure 5.1. In each experiment, participants saw both causal and noncausal animations. The two kinds of animations were designed to be as similar as possible. In Experiments 1–3, the causal animations depicted

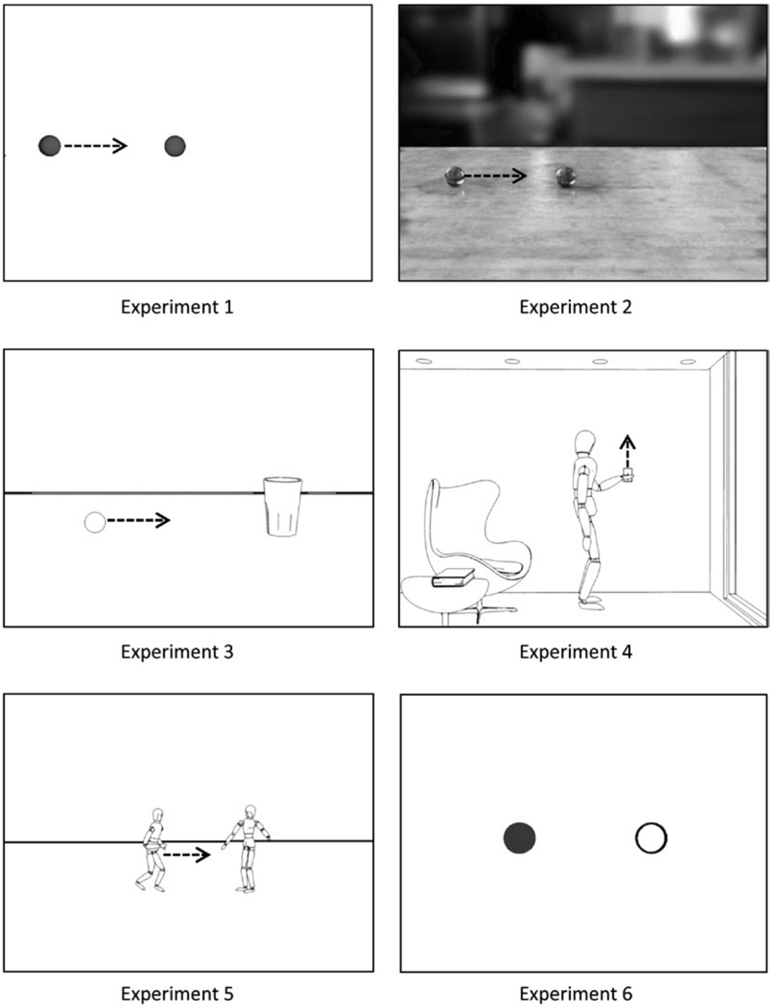

Figure 5.1 Frames from the causal animations used in experiments 1 through 6. In Experiment 1, shown in the top left panel, the ball on the left hits the ball on the right, sending it into motion. In Experiment 2, shown in the top right panel, the motions were the same as in Experiment 1, except the surfaces were near-photorealistic. In Experiment 3, the surfaces were the same as in Experiment 2, except the second marble was replaced with a glass cup that shattered. In Experiment 4, the person flips a switch and the lights in the ceiling turn on; the animation depicted a near-photorealistic scene. In Experiment 5, the person on the left approaches the one on the right, who directs that person to turn to the right; the animation depicted a desert scene. In Experiment 6, there is no motion, rather, the circle on the left turns solid, and then a few moments later, the circle on the right turns solid.

collision events. In Experiment 1, in particular, the background was black and a red ball hits another red ball, sending it into motion. The noncausal variant of this animation showed a single ball move across the screen at the same exact rate as the balls in the causal animation. In Experiment 2, causal and noncausal animations were exactly the same as those used in Experiment 1, except that the animations were rendered using near-photorealistic surfaces. The balls were blue marbles that rolled on top of a marble countertop, and an out-of-focus background suggested various kinds of kitchen appliances, a window, and a sink. The causal and noncausal animations in Experiment 3 were much the same as those used in Experiment 2, except that the second marble in the causal animation was replaced with a small, clear glass cup that shattered upon impact. In the noncausal version of this change-of-state event, the glass was removed and the ball traveled the exact same path traveled in the causal version of the event.

In all three experiments, the trial structure was the same. In each trial, participants held the haptic controller and saw the same animation four times. The first three times, the animation played at different speeds, randomly chosen, such that the animation lasted 540, 1440, 2340 or 3240 ms. We showed the animation several times in order to "build up" the sense of force. The fourth time the animation played, it lasted an intermediate amount of time, 1800 ms. At the end of the last animation, the last frame of the animation was paused, and the haptic controller moved 100, 200, 300, 400, or 500 ms after the onset of the last frame. When they felt the controller move, participants were to press a button on the controller to indicate that they had felt a force. The movement times were varied so that participants could not predict exactly when the controller would move. The force generated by the controller was very small, specifically 1.5 N for 20 ms, which, phenomenologically, produced a very faint impression on the hand, but clearly above the sensory threshold for touch. There were 20 practice trials, half causal, half noncausal, and 40 experimental trials, again, half and half.

The main prediction was that "seeing" a causal event would affect people's speed at detecting a force, most likely in the direction of decreasing their reaction times, giving rise to a type of "priming" effect. While such a result would support the hypothesis that people infer forces when they see causal events, it could also be consistent with several other less interesting possibilities. In particular, such a result could arise if the causal events were better predictors of the onset of the force than the noncausal events, despite our efforts to discourage such predictive processes. Alternatively, the causal events could have been more interesting than the noncausal events, hence increasing people's arousal level and ultimately decreasing their response times.

To guard against such possibilities, two control conditions were added to the experiments. These conditions were exactly the same as that described above except that, instead of a force, participants were subject to either an auditory or visual signal. In the auditory signal control condition, participants heard a brief electronic sound through a set of earphones. In the visual signal control condition, a dot was briefly flashed above the last object at the very end of the animations. In both conditions, the participants' task was to press the button on the haptic controller as soon as they either saw the dot or heard the sound. The controller did not move in either of these conditions. These conditions are important because if effects are found in the force condition, but they are due to uninteresting reasons, such as predictability or arousal levels, then the same effects should also be observed in the visual and auditory conditions. In contrast, if there is an effect in the force condition and not in the auditory and visual control conditions, the overall pattern of results will suggest that the effect of seeing a causal event is specific to the touch modality, just as we are predicting. In sum, our main prediction was that people would be faster to detect a force after seeing a causal than noncausal event, and that this effect would only be observed in the force condition.

The predicted results were obtained in all the experiments. The results from Experiments 2 are representative of all of the experiments. As shown in Figure 5.2, people responded faster to a force against their hand after seeing

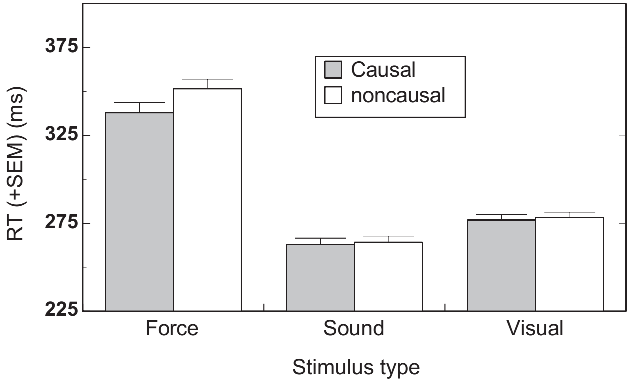

Figure 5.2 Results from Experiment 2 showing reaction time to respond to a force, sound, or visual stimulus after watching a causal or noncausal animation. Error bars indicate standard errors of the mean.

a causal than noncausal event, $t(24) = 2.38$, $p = 0.025$. Importantly, this difference cannot be explained as an effect due to greater predictability of the signal after seeing the causal than noncausal event, or to greater arousal after seeing the causal versus noncausal event, because times to respond to a sound or visual stimulus did not differ after watching a causal or noncausal event. Rather, watching causal events only had an effect on speed to detect a force.

In Experiment 2, the reaction time to respond to a force after watching a causal animation minus the time to respond to a force after watching a noncausal animation was −13.5 ms; in other words, participants were 13.5 ms faster to respond to a force after viewing a causal animation than a noncausal animation. There was no evidence for such a difference in the sound ($D = -1.35$) or visual ($D = -1.47$) conditions. The same set of differences for the other experiments are listed in Table 5.1, and as can be seen, the pattern was the same across the other experiments. In Experiments 1 and 3 as well, people were statistically faster to report detecting a force after watching a causal animation than after watching a noncausal animation, but there was no evidence for a similar difference when detecting a sound or visual signal. Altogether, the results from Experiments 1–3 suggest that when people see a causal event involving physical forces, they perceive these forces in a rather direct manner.

5.2. Forces in the Perception of Indirect and Social Causation

It could be argued that the events used in Experiments 1–3 were special in that people had direct access to the underlying mechanism of the causation, which involved direct physical contact. In many everyday causal relations, we do not have access to the underlying mechanisms behind the causation. A reasonable question, then, is whether forces are experienced in the case of events in which the underlying physical mechanism is hidden. This question was examined in Experiment 4. The procedure, trial structure and experimental design were the same as in the previous experiments. The only difference was that the experiment used materials in which the causal mechanism was hidden; specifically, in the causal condition a person flipped a switch and the ceiling lights came on and in the noncausal condition a person flipped a switch and the ceiling lights remained on. Hence, the two animations ended up exactly the same, namely, with the lights on. The animations used in this experiment were near-photorealistic, so people could easily differentiate when the lights were on or off. As shown in Table 5.1, the pattern of results was the same as in the previous experiments. Participants were faster

Table 5.1 Difference in RT to Indicate Detecting a Force, Sound or Visual Signal after Watching a Causal versus Noncausal Animation for Experiments 1–5 in Milliseconds

	Stimulus type		
	Force	**Sound**	**Visual**
Experiment 1: schematic collision	−9.2	0.21	−0.72
Experiment 2: realistic collision	−13.5	−1.35	−1.47
Experiment 3: shattering	−7.6	−1.01	−2.019
Experiment 4: turning on a light	−14.8	1.28	−3.58
Experiment 5: social causation	−15.1	−0.070	−2.49

to respond to a force after watching the causal than noncausal event, but there was no evidence for a similar difference in the sound and visual conditions. The results from this experiment suggest that people experience forces in causal situations even when the physical forces are hidden.

In Experiment 5, we examined an even more abstract type of causation, that of social causation. The procedure, trial structure, and design were the same as in the previous experiments. In the cause condition, participants saw a person direct another person to change their path of motion. In the noncausal condition, participants saw a person travel the same path of motion as in the causal condition, but without another person directing them to change their path. As in previous experiments, the animations included photorealistic surfaces, in this case, a desert scene with a large open sky. As shown in Table 5.1, the pattern of results mirrored that of the earlier studies. Participants were significantly faster to report a force after watching the causal events than the noncausal events, and this difference only occurred in the force condition. The results imply that social causal events are experienced in a manner similar to how people experience physical causal events.

Across a relatively wide range of situations, we found that causal events were associated with the experience of force. Interestingly, the results suggest that the perception of force affected people's touch sensitivity and not their motor planning. Had the perception of force affected motor activity we should have seen faster RTs after seeing causal than noncausal events not only in the force condition, but also in the sound and visual conditions. The effect should have been present in all three conditions because in all three conditions participants had to engage in the motor activity of pressing a button. The results suggest, then, that when people perceive forces from visual stimuli, they "empathize" with the object that suffers the effect, the patient, which sensitizes their sense of touch, and not with the object that brings about the event, the agent. Thus, our results are more consistent with

Fales' (1990) patient-oriented account of force perception than White's (1999, 2006, 2012a), Reid's (1788/2010), Maine de Biran's (Jammer, 1957) and Piaget's (1930/1969) agent-oriented accounts.

5.3. Correlations and the Sense of Force

At the beginning of the paper, we noted that there is a difference between correlations that are causal and those that are noncausal. If forces are absolutely necessary for causation, then maybe the ingredient that makes a correlation causal is whether it involves force. This possibility was examined in an experiment involving abstract correlations. Specifically, participants (N = 50) saw animations showing two circles, like those shown in the last panel in Figure 5.1. The circle on the left can be viewed as the "cause" (C) and the circle on the right as the "effect" (E). In half of the trials, the cause turned solid, followed a few moments later by the effect turning solid. In 1/5 of the trials, the cause did not turn solid, but the effect did. Finally, in the remaining trials, neither circle turned solid. Based on these frequencies, the probability of the effect given the cause, $P(E|C)$, equaled 1, and the probability of the effect given the absence of the cause, $P(E|\neg C)$, equaled 0.4. These probabilities entail that the probability of the effect given the cause is greater than the probability of the effect in the absence of a cause, that is, $P(E|C) > P(E|\neg C)$; thus, the probabilities entail that the effect correlated positively with the cause.

As in the previous experiments, trials consisted of sets of four animations. However, in the current experiment, participants indicated only whether they felt a force. One other difference from the previous experiments is that at the end of the experiment, participants were asked several questions. First, they were asked whether it seemed that the circle on the left sometimes caused the circle on the right to change. Participants were also asked to estimate the percentage of times the circle on the right changed when the circle on the left changed, thus providing an estimate of $P(E|C)$, as well as the percentage of times the circle on the right changed when the circle on the left did NOT change, providing an estimate of $P(E|\neg C)$. Higher estimates for $P(E|C)$ than for $P(E|\neg C)$ would imply that participants noticed the correlation between the cause and effect. In sum, the questions at the end of the experiment allowed us to determine whether participants noticed a correlation and whether they felt the correlation was causal. In addition, because we also measured participants' responsiveness to forces, we could examine whether their judgments of causation were associated with their responsiveness to forces.

In Experiment 6, there were two conditions. Half of the participants were given mechanism information. Specifically, they were told that "The light on the left is linked to the one on the right through a long sequence of circuits." The remaining participants were simply told that they would see a series of animations.

One of the main predictions was that people would be sensitive to the correlational structure of the materials in both the mechanism and no-mechanism conditions. A second main prediction was that people would be more likely to say that the first circle caused the second circle to change in the mechanism condition than in the no-mechanism condition. This prediction was based on pilot research showing that if people are given extremely sparse materials, they often fail to consider the possibility of a causal relationship unless they are given a cover story suggesting the existence of causal relation. The experiment was designed, then, to create a situation in which two groups of people encoded the same correlation, but only one of the groups would view the correlation as causal. The last main prediction concerned participants' responsiveness to the forces generated by the haptic controller. If force is necessarily a part of the notion of causation, we should find greater responsiveness to forces in the mechanism condition than in the no-mechanism condition.

The results were as predicted. Firstly, as expected, participants noticed the correlation between the cause and effect circles in both conditions and to the same degree in both conditions. In support of this observation, the probably of the effect given the cause, $P(E|C)$, was significantly greater than the probability of the effect in the absence of the cause, $P(E|\neg C)$, in both the mechanism, $t(24) = 3.09$, $p < 0.05$, and no-mechanism conditions, $t(24) = 3.69$, $p < 0.01$, and there was no evidence that the difference in the probability estimates in the mechanism condition ($D = 22.5$) differed from the difference in probability estimates in the no-mechanism condition ($D = 22.4$), $F(1,48) = 0.026$.

The second major prediction was also borne out, in that participants endorsed the statement that the first circle seemed to cause the second circle to change more often in the mechanism condition ($M = 76\%$) condition than in the no-mechanism condition ($M = 44\%$), $t(48) = 2.39$, $p < 0.05$. Hence, participants picked up on the correlation between the circles in both the mechanism and no-mechanism conditions, but in terms of causation, the modal response in the mechanism condition was that it was causal, whereas in the no-mechanism condition it was noncausal. The question, then, is what makes a correlation seem causal? Turning to our last major prediction, as expected, participants responded faster to a force in the mechanism condition ($D = -22.9$ ms), $t(24) = 4.43$, $p < 0.001$, than in the no-mechanism condition, ($D = -11.28$ ms), $t(24) = 1.88$, $p = 0.072$. Interestingly, dividing the participants in the no-mechanism condition according to whether they viewed the two circles as causally connected reveals that sensitivity to force was much greater in those who reported feeling there was a causal connection ($D = -21.26$ ms) than in those who did not feel there was a causal connection ($D = -2.8$). This implies that the marginally significant effect of force in the no-mechanism condition was driven completely by those who reported feeling there was a causal connection between the circles. The results paint a clear picture: the difference between correlations that are viewed as causal and those that are not viewed as causal is the feeling of force.

6. THE FEELING OF CAUSATION IN THE ABSENCE OF MECHANISM: A DUAL PROCESS APPROACH

The results discussed above suggest that people can feel a sense of force in the absence of a clear understanding of mechanism. This is surprising finding because if the underlying mechanism is not known, there is some question why forces should be felt. One possibility is that the perception of forces from visual materials is initially tied, developmentally speaking, to situations in which the mechanism is clearly present, that is, to situations in which physical contact, or a chain of physical contacts is present. With experience, people may learn to associate the existence of forces with only a subset of the properties in such scenes, like temporal contiguity. Such properties might develop into cues or heuristics for inferring the presence of forces. Eventually, such cues might lead people to feel forces even when knowledge of the underlying mechanism is not available. Moreover, to the extent that force impressions are based on heuristics, it should be expected that people will sometimes sense forces—and have a related feeling of causation—even when such forces are not actually present. By definition, heuristics are not infallible; they merely serve as rough guides to the existence of certain features of the environment. This proposal is supported by the existence of causal illusions, such as those that sometimes accompany electrical blackouts.

6.1. Explaining Causal Illusions in a Dual-process Framework

Back in July of 1977, a lightning strike hit the Buchanan South electrical substation on the Hudson River, tripping two circuit breakers in the northern suburbs of Westchester County, New York. The event triggered a series of breakdowns that within 15 min left New York City in darkness. Interviews with "survivors" (Sparrow, 1999) indicated there was keen interest in the causes behind this event. Some attributed the blackout to equipment failure and others to unidentified flying object (UFOs) or to a Soviet invasion. Especially interesting, some felt, at least momentarily, that the blackout was caused by their own actions, like the opera singer who touched a door knob at the exact instant the lights turned off, or the child who accidently hit a ceiling light fixture with her paddle ball, again at the exact moment everything went dark. As one of the 1997 survivors exclaimed after plugging in a toaster, "I blew out the whole neighborhood!" (Sparrow, 1999). Of course, touching a knob, hitting a ceiling light or plugging in an appliance cannot cause a massive blackout, but when the conditions are exactly right, a feeling of causation may emerge nonetheless.

Interestingly, in situations like blackouts, people may experience feelings of causation while at the same time knowing that such feelings are unwarranted. The fact that people can have conflicting opinions about the existence of a causal relationship is consistent with the idea that causal understanding might be based on two processes: an intuitive process that is fast and automatic and a reflective process that is slow and strategic. The intuitive process would be based on perceptual heuristics that give rise to a general sense of force and causation. The slow process would be one that depends on a careful analysis of the situation to determine whether there exists a mechanism for connecting the candidate cause and effect. The slow process would not necessarily involve checking every possible link in a chain. It might be satisfied with knowledge of a physical connection. However, in order to know whether causation is actually present, at the level of certainty required in science, for example, a detailed analysis of the mechanism would require knowledge not just of a physical connection, but also the forces or energies that are enabled by the physical connection.

The distinction between intuitive and reflective processes is not new. It maps directly unto a prominent distinction made in the perception, reasoning, and social cognition literature. According to dual-processing theories, System 1 processing refers to computations that are implicit, unconscious, and heuristic, while System 2 processing refers to computations that are explicit, analytic, and rule-based (Evans, 2008; Kahneman, 2003; Sloman, 1996; Stanovich & Toplak, 2012; Stanovich & West, 2000). Moreover, the distinction between intuitive and reflective processes aligns well with the distinction often made (usually implicitly) in the causation literature between perceived and judged causation (Schlottmann & Shanks, 1992). Perceived causality is causality acquired directly from perceptual experience without aid from background knowledge (Leslie, 1988; Michotte, 1963; Rips, 2011; White, 2006). In contrast, judged causality is causality learned through elaboration and inference (Michotte, 1963; White, 2006; Schlottmann et al., 2006). While a distinction between perceived and judged causation has been noted in the literature, its empirical foundations have yet to be firmly established.

The idea that causal understanding might be based on two kinds of process, intuitive and reflective, offers a potential solution to the problem of how people might represent causal relations in terms of forces in the absence of knowledge of the underlying mechanism. Specifically, in particular situations, various properties of the environment might serve as cues to the presence of forces. One cue, in particular, would be temporal contiguity between an agent's actions and a particular effect. In line with dual-processing theories, impressions based on such cues might last only a moment. Moreover, the initial causal impressions should be especially sensitive to the properties of the cues. We would expect, then, that temporal contiguity might have a larger impact on people's momentary causal judgments than on their reflective judgments. This prediction was tested in the following experiment.

6.2. An Initial Test of the Dual Process View of Causal Understanding

In this experiment, participants (N = 104) saw a single animation depicting two main events: a person hitting a fire hydrant with a stick and an illuminated town going dark. Snapshots of two moments of these events are shown in Figure 5.3. The left panel of this figure shows a lit-up town in the background and, in the foreground, a person preparing to hit a fire hydrant with a stick. The panel on the right shows the situation at a later point in the animation, with the town completely dark. After watching the animation, participants were asked to imagine that they were the person in the scene and answer two questions: "Would you feel for a moment that the striking of the fire hydrant caused the lights to go out?" and "Would you ultimately conclude that the striking of the fire hydrant caused the lights to go out?" Participants recorded their answer on an eight-point scale in which 0 equaled "Definitely not" and 7 equaled "Definitely yes". For the sake of discussion, we report the results simply in terms of the proportion of times people reported "yes," that is, the proportion of times they gave a rating of 4 or higher.

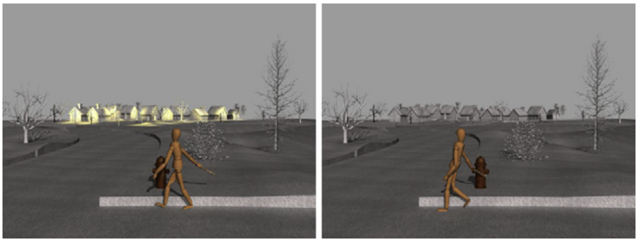

Figure 5.3 In the picture on the left, a person prepares to hit a fire hydrant with a stick, while in the picture on the right, the fire hydrant has been hit and the lights in the town have turned off. For color version of this figure, the reader is referred to the online version of this book.

We predicted that our blackout scenario would produce some of the same reactions reported during the 1977 New York City blackout, that is, our blackout scenario would give rise to a causal illusion. Specifically, we predicted that if the town went dark immediately after the person hit the fire hydrant, this would give rise to a causal impression in which people would *momentarily feel* as if the person in the scene caused the blackout. However, if people were asked to give a causal judgment by having them decide whether they would ultimately conclude that the person caused the town to go dark, we predicted that they would say "no", that is, that they would recognize that the feeling of causation was not a true representation of what had happened.

In addition to testing this main prediction, the experiment was designed to test one further prediction, specifically, that temporal contiguity would have a larger effect on people's initial causal impressions than on their later causal judgments. The prediction is based in part on work showing that temporal contiguity has an effect on people's causal impressions of collisions events (Morris & Peng, 1994; Oakes & Kannass, 1999; Schlottmann & Anderson, 1993; Schlottmann & Shanks, 1992) than on their causal judgments of correlations (Schlottmann & Shanks, 1992). Such an effect is important because it would help establish the existence of two kinds of processes underlying causal understanding.

To test whether temporal contiguity had a larger effect on initial impressions than on more reflective judgments, participants were randomly assigned to one of four conditions (all $N = 26$). In the first condition, the town went dark immediately after the person hit the fire hydrant with the stick. In the second and third conditions, the town lights turned off one and 2 s respectively after the person hit the fire hydrant. Finally, in a

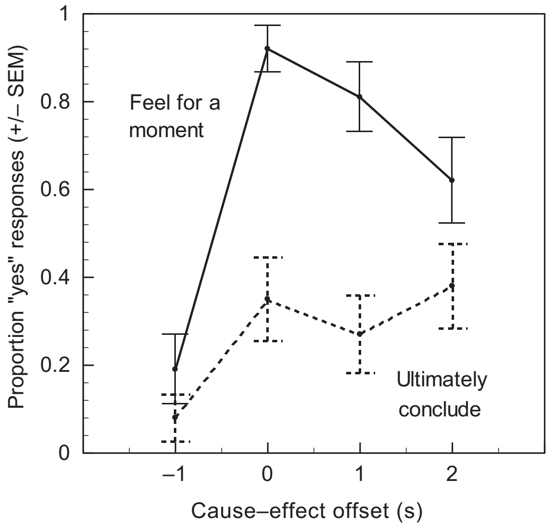

Figure 5.4 Proportion of "yes" responses to questions asking whether participants "felt" and "ultimately concluded" that the blackout event depicted causation for four different cause–effect offsets: the effect occurred before the cause by 1 s (–1), the effect occurred at exactly the same time as the cause (0), the effect occurred 1 s after the cause (1), and the effect occurred 2 s after the cause. The error bars represent standard errors of the mean.

fourth condition, the town lights turned off 1 s *before* the person hit the fire hydrant. In this fourth condition, the "effect" occurred before the cause, so it was predicted that participants' impressions and judgments of causation should be very low. This condition was included to serve as a baseline condition for interpreting the results in the other conditions.

As shown in Figure 5.4, the results were in line with our predictions. Perhaps most strikingly, participants' causal impressions patterned very differently from their causal judgments. For example, when the town darkened immediately after being hit (i.e. cause–effect offset = 0), 92% of the participants reported feeling a sense of causation, but only 35% reported that they would ultimately conclude that the striking of the fire hydrant caused the town to go dark. Another key difference between participants' causal impressions and causal judgments was that temporal contiguity had a large impact on their causal impressions but not on their causal judgments. As the delay between the striking and the town darkening increased, participants' causal impressions decreased from 92% in the 0 delay condition to 62% in the 2-s delay condition, a significant difference. In contrast, participants' causal judgments stayed essentially the same across these two conditions, with 35%

yeses in the 0 delay condition and 38% yeses in the 2-s delay condition. As expected, participants' causal impressions and judgments were very low when the "effect" occurred before the "cause." Participants' causal judgments were lower in this condition than in the 0 and 2-s delay conditions. This finding implies that the absence of change in participants' causal judgment ratings across the different time offsets cannot be explained as due to their ratings being at floor. Moreover, they imply that participants may have found ways to explain how hitting a fire hydrant might result in a blackout.

Several conclusions can be drawn from these results. First, the results provide support for a distinction between intuitive and reflective processes in causal understanding. Causal impressions emerge spontaneously with little connection to prior causal knowledge. Causal judgments, in contrast, are based on more strategic thought involving prior knowledge. A second conclusion is that people may feel a strong impression of causation even when the generative process is unclear. As noted earlier, this phenomenon may explain how a force-based view of causation is possible when knowledge of the underlying mechanism is not available. Cues in the environment may trigger the impressions of forces that give rise to the impression of causation, even when the impression of causation is unwarranted. Thirdly, the results indicate that causal impressions are not limited to the kinds of scenarios originally studied by Michotte (1946/1963). In the launching event, both temporal and spatial contiguity were found to be important for the impression of causation (Schlottmann & Anderson, 1993; Schlottmann & Shanks, 1992; Scholl & Tremoulet, 2000; White, 2011). In the blackout scenario, the spatial arrangement of the A and B objects was quite different from Michotte's materials (1946/1963), yet an impression of causation was found. The results demonstrate that the causal impression can emerge from a much wider range of events than has generally been assumed.

7. POTENTIAL PROBLEMS FOR A FORCE-BASED VIEW OF CAUSATION

The evidence from a variety of sources offers support for the proposal that causal understanding is based on the feeling of force. There is, however, at least one study that raises a possible challenge to this proposal. In particular, recent findings from White (2011) have been interpreted as showing that impressions of causation and of force are independent of each other. This conclusion was based on the finding that participants' ratings of causation and force sometimes patterned differently, but not always. In the first of several experiments, White (2011) found that impressions of force decreased with increases in time delay, just as Michotte (1963) found with impressions of causation. Thus, with respect to time, White (2011) found that impressions of force greatly resembled impressions of causation. However, in White's (2011) Experiment 4, he found that ratings of causation and force differed. Specifically, he found that ratings of force were weakly affected by differences in gap size and type of intermediary, while ratings of causation were greatly affected by these properties. These inconsistencies led White (2011) to conclude that the impression of causation is not based on the same process that underlies the impression of force.

It should be emphasized that White's (2011) experiment was probably the first to directly measure both impressions of causation and force, making it an important contribution to the field. It should also be noted, however, that the instructions used in White's (2011) Experiment 4 were not parallel across the conditions. Participants in the causation condition were told that events with gaps *were not* consistent with causation in real life, while participants in the force condition were told the opposite, namely, that gaps *were* consistent with forces in the real world because forces can be transmitted across gaps. Given these differences, it is certainly possible that the differences in participants' impressions of causation and their impressions of force were due to the differences in the instructions.

But even if the rating differences were not due to differences in the instructions, there are several other reasons why White's (2011) results do not rule out causation being based on force. As noted in the preceding section, ratings of causation may be based on either intuitive or reflective processes, or both. If ratings of force differ from ratings of causation, the difference could be due to the kind of causal process being tapped during the rating. As shown in the research on blackouts, the same event can be associated with two very different ratings of causation. One final reason why White's (2011) results need not rule out a causation–force connection is because the difference between the two kinds of ratings could be due to the way forces were measured. In White (2011), forces were measured using explicit verbal ratings, whereas in the haptic experiments described earlier, forces were measured using implicit reaction times. It remains an open question whether these two measures of force capture the same impression. To the extent that they do not, the two measures might lead to very different conclusions about the relationship between causation and force. Given all of these concerns, the conclusion that causation is not based on force seems, at best, premature. In White's (2012a, 2012b) most recent writings, it seems he would agree.

8. CONCLUSIONS

The idea that causation might be based on forces is one of the oldest and longest-lasting theories of causation. Major criticisms of this theory have focused on issue of learnability and whether such a theory can be applied to abstract causal relations. Recent work on the theory suggests that these two challenges can be met. With regards to learnability, the claim was that if causal relations were based on forces, then they could not be learned because forces are not part of people's sensory experience. While it is true that forces cannot be seen, this does not entail that they are absent from people's sensory experience because forces can definitely be felt, and because they can be felt, they can ultimately be learned. The sense of touch, proprioception, and balance provide a foundation for the notion of force, and then by extension, the concept of causation. The feeling of causation they provide may be extended to causal relations perceived through the visual modality. For causal relations perceived through vision, the sense of touch provides a sensory experience that unifies the vast range of visual patterns we associate with causation. With regards to the applicability of force-based theories to abstract causation, the experiments described in this paper show that a force-based approach can be extended to abstract causation. With time, the perception of forces becomes associated with cues to causation that allow for impressions of causation in the absence of knowledge of the underlying mechanism. Inferring forces from cues will sometimes lead to causal illusions, such as the illusion that a person caused an entire city to darken simply by hitting a fire hydrant. More often than not, however, these cues will lead people to infer causal relations that are actually present. According to this proposal, causal understanding remains physical in its phenomenology, even as its ontology is extended from the physical to the abstract. The great leap forward regarding causal understanding is in our ability to use secondary sensations—sensations experienced through another modality—to create conceptual structure.

REFERENCES

Ahn, W., & Bailenson, J. (1996). Causal attribution as a search for underlying mechanisms: An explanation of the conjunction fallacy and the discounting principle. *Cognitive Psychology*, *31*, 82–123.

Ahn, W., & Kalish, C. W. (2000). The role of mechanism beliefs in causal reasoning. In F. C. Keil, & R. A. Wilson (Eds.), *Explanation and cognition* (pp. 199–225). Cambridge, MA: MIT Press.

Ahn, W., Kalish, C. W., Medin, D. L., & Gelman, S. A. (1995). The role of covariation versus mechanism information in causal attribution. *Cognition*, *54*, 299–352.

Aristotle. (1999). *Aristotle Physics: Book VIII (D. Graham, Trans.)*. New York: Oxford University Press.

Aristotle. (2011). *The Eudemian Ethics (A. Kenny, Trans.)*. New York: Oxford University press.

Aronson, J. L. (1971). On the grammar of "cause". *Synthese*, *22*, 414–430.

Bigelow, J., Ellis, B., & Pargetter, R. (1988). Forces. *Philosophy of Science*, *55*, 614–630.

Bigelow, J., & Pargetter, R. (1990). Metaphysics of causation. *Erkenntnis*, *33*, 89–119.

Bullock, M., Gelman, R., & Baillargeon, R. (1982). The development of causal reasoning. In W. Friedman (Ed.), *The developmental psychology of time* (pp. 209–255). London: Academic Press.

Blakemore, S. J., Bristow, D., Bird, G., Frith, C., & Ward, J. (2005). Somatosensory activations during the observation of touch and a case of vision-touch synaesthesia. *Brain*, *128*, 1571–1583.

Cheng, P. W. (1997). From covariation to causation: a causal power theory. *Psychological Review*, *104*, 367–405.

Cheng, P. W., & Novick, L. R. (1991). Causes versus enabling conditions. *Cognition*, *40*, 83–120.

Cheng, P. W., & Novick, L. R. (1992). Covariation in natural causal induction. *Psychological Review*, *99*, 365–382.

Conditt, M. A., Gandolfo, F., & Mussa-Ivaldi, F. A. (1997). The motor system does not learn the dynamics of the arm by rote memorization of past experience. *Journal of Neurophysiology*, *78*, 554–560.

Davidson, P. R., & Wolpert, D. M. (2004). Internal models underlying grasp can be additively combined. *Experimental Brain Research*, *155*, 334–340.

Dowe, P. (2000). *Physical causation*. Cambridge, England: Cambridge University Press.

Ebisch, S. J.H., Perrucci, M. G., Ferretti, A., Del Gratta, C., Romani, G. L., & Gallese, V. (2008). The sense of touch: embodied simulation in a visuotactile mirroring mechanism for observed animate or inanimate touch. *Journal of Cognitive Neuroscience*, *20*, 1611–1623.

Ellis, R., & Lederman, S. J. (1999). The material-weight illusion revisited. *Perception & Psychophysics*, *61*, 1564–1576.

Evans, J. St. B.T. (2008). Dual-processing accounts of reasoning, judgment, and social cognition. *Annual Review of Psychology*, *59*, 255–278.

Fair, D. (1979). Causation and the flow of energy. *Erkenntnis*, *14*, 219–250.

Fales, E. (1990). *Causation and universals*. London: Routledge.

Flanagan, J., & Beltzner, M. A. (2000). Independence of perceptual and sensorimotor predictions in the size-weight illusion. *Nature Neuroscience*, *3*, 737–741.

Gordon, A. M., Forssberg, H., Johansson, R. S., & Westling, G. (1991). Visual size cues in the programming of manipulative forces during precision grip. *Experimental Brain Research*, *83*, 477–482.

Hamilton, A., Joyce, D. W., Flanagan, J. R., Frith, C. D., & Wopert, D. M. (2007). Kinematic cues in perceptual weight judgment and their origins in box lifting. *Psychological Research*, *71*, 13–21.

Harré, R., & Madden, E. H. (1975). *Causal powers: a theory of natural necessity*. Oxford: Blackwell.

Heidegger, M. (1981/1995). *Aristotle's metaphysics 1–3: On the essence and actuality of force (translated by W. Brogan & P. Warnek)*. : Indiana University Press. (Original published in 1981).

Hinder, M. R., & Milner, T. E. (2003). The case for an internal dynamics model versus equilibrium point control in human movement. *Journal of Physiology*, *549*, 953–963.

Hubbard, T. L., & Ruppel, S. E. (2002). A possible role of naïve impetus in Michotte's "launching effect" evidence from representational momentum. *Visual Cognition*, *9*, 153–176.

Hume, D. (1748/1975). Enquiry concerning human understanding. In L. A. Selby-Bigge (Ed.), *Enquiries concerning human understanding and concerning the principles of morals* (3rd ed.). Oxford: Clarendon Press. revised by P. H. Nidditch.

Imamizu, H., Uno, Y., & Kawato, M. (1995). Internal representations of the motor apparatus: implications from generalization in visuomotor learning. *Journal of Experimental Psychology: Human Perception and Performance*, *21*, 1174–1198.

Jammer, M. (1957). *Concepts of force*. Cambridge, MA: Harvard University Press.

Jones, L. A. (2000). Kinesthetic sensing. In *Proceedings of workshop on human and machine haptics* (pp. 1–10). Cambridge, MA: MIT Press.

Jones, L. A., & Piateski, E. (2006). Contribution of tactile feedback from the hand to the perception of force. *Experimental Brain Research*, *168*, 298–302.

Kahneman, D. (2003). A perspective on judgment and choice. *American Psychologist*, *58*, 697–720.

Kawai, S., Henigman, F., MacKenzie, C. L., Kuang, A. B., & Faust, P. H. (2007). A reexamination of the size-weight illusion induced by visual size cues. *Experimental Brain Research*, *179*, 443–456.

Kawato, M. (1999). Internal models for motor control and trajectory planning. *Current Opinion in Neurobiology*, *9*, 718–727.

Keysers, C., Kaas, J. H., & Gazzola, V. (2010). Somatosensation in social perception. *Nature Reviews*, *11*, 417–428.

Keysers, C., Wicker, B., Gazzola, V., Anton, J., Fogassi, L., & Gallese, V. (2004). A touching sight: SII/PV activation during the observation and experience of touch. *Neuron*, *42*, 335–346.

Kotovsky, L., & Baillargeon, R. (1998). The development of calibration-based reasoning about collision events in young infants. *Cognition*, *67*, 311–351.

Kotovsky, L., & Baillargeon, R. (2000). Reasoning about collisions involving inert objects in 7.5-month-old infants. *Developmental Science*, *3*, 344–359.

Leslie, A. M. (1988). The necessity of illusion: perception and thought in infancy. In L. Weskrantz (Ed.), *Thought without language* (pp. 185–210). Oxford: Oxford Science Publications.

Leslie, A. M. (1994). ToMM, ToBy, and agency: Core architecture and domain specificity. In L. Hirschfield, & S. Gelman (Eds.), *Mapping the mind: Domain specificity in cognition and culture* (pp. 119–148). Cambridge, England: Cambridge University Press.

Marmodoro, A. (2007). The union of cause and effect in Aristotle: physics III 3. *Oxford Studies in Ancient Philosophy*, *32*, 205–232.

Meyer, K., Kaplan, J. T., Essex, R., Damasio, H., & Damasio, A. (2011). Seeing touch is correlated with content-specific activity in primary somatosensory cortex. *Cerebral Cortex*, *21*, 2113–2121.

Michotte, A. E. (1963). *The perception of causality (translated by T. R. Miles, & E. Miles)*. London: Methuen. (Original published in 1946).

Milner, T. E., & Franklin, D. W. (2005). Impedance control and internal model use during the initial stage of adaptation to novel dynamics in humans. *Journal of Physiology*, *567*, 651–664.

Morris, M. W., & Peng, K. (1994). Culture and cause: American and Chinese attributions for social and physical events. *Journal of Personality and Social Psychology*, *67*, 949–971.

Oakes, L. M., & Kannass, K. N. (1999). That's the way the ball bounces: Infants' and adults' perception of spatial and temporal contiguity in collisions involving bouncing balls. *Developmental Science*, *2*, 86–101.

Ohta, K., & Laboissière, R. (2006). Underlying principles of trajectory formation for human movement in dynamical environments. *International Congress Series*, *1291*, 97–100.

Ott, W. (2009). *Causation and laws of nature in early modern philosophy*. New York: Oxford University Press.

O'Neill, E. (1993). Influxus physicus. In S. Nadler (Ed.), *Causation in early modern philosophy* (pp. 27–57). : Penn State University Press.

Panarese, A., & Edin, B. B. (2011). Human ability to discriminate direction of three-dimensional force stimuli applied to the finger pad. *Journal of Neurophysiology*, *105*, 541–547.

Papaxanthis, C., Pozzo, T., & McIntyre, J. (2005). Kinematic and dynamic processes for the control of pointing movements in humans revealed by short-term exposure to microgravity. *Neuroscience*, *135*, 371–383.

Piaget, J. (1930/1969). *The child's conception of physical causality. (translated by Marjorie Gabain, 1969).* Totowa, NJ: Littlefield, Adams & Co.

Pihko, E., Nangini, C., Jousmäki, V., & Hari, R. (2010). Observing touch activates human primary somatosensory cortex. *European Journal of Neuroscience*, *31*, 1836–1846.

Reid, T. (1788/2010). Sections from essays on the active powers of man. In T. Nadelhoffer, E. Nahmias, & S. Nichols (Eds.), *Moral psychology: Historical and contemporary readings* (pp. 246–250). Wes Sussex, United Kingdom: Blackwell Publishing Ltd.

Reinkensmeyer, D. J., Emken, J. L., & Crammer, S. C. (2004). Robotics, motor learning, and neurological recovery. *Annual Review of Biomedical Engineering*, *6*, 497–525.

Rips, L. J. (2011). Causation from perception. *Perspectives on Psychological Science*, *6*, 77–97.

Runeson, S., & Frykholm, G. (1983). Kinematic specification of dynamics as an informational basis for person-and-action perception: expectation, gender recognition, and deceptive intention. *Journal of Experimental Psychology: General*, *112*, 585–615.

Salmon, W. (1994). Causality without counterfactuals. *Philosophy of Science*, *61*, 297–312.

Salmon, W. (1998). *Causality and explanation*. Oxford, England: Oxford University Press.

Saxe, R., & Carey, S. (2006). The perception of causality in infancy. *Acta Psychologica*, *123*, 144–165.

Schlottmann, A., & Anderson, N. H. (1993). An information integration approach to phenomenal causality. *Memory and Cognition*, *21*, 785–801.

Schlottmann, A., Ray, E., Mitchell, A., & Demetriou, N. (2006). Perceived physical and social causality in animated motions: spontaneous reports and ratings. *Acta Psychologica*, *123*, 112–143.

Schlottmann, A., & Shanks, D. (1992). Evidence for a distance between judged and perceived causality. *Quarterly Journal of Experimental Psychology*, *44A*, 321–342.

Scholl, B. J., & Tremoulet, P. D. (2000). Perceptual causality and animacy. *Trends in Cognitive Sciences*, *4*, 299–309.

Shultz, T. R. (1982). Rules of causal attribution. *Monographs of the Society for Research in Child Development*, *47*(1, Serial No. 194), 1–51.

Schulz, L., Kushnir, T., & Gopnik, A. (2007). Learning from doing: intervention and causal inference. In A. Gopnick, & L. Schulz (Eds.), *Causal learning: Psychology, philosophy, and computation* (pp. 67–85). Oxford: Oxford University Press.

Shadmehr, R., & Mussa-Ivaldi, F. A. (1994). Adaptive representation of dynamics during learning of a motor task. *Journal of Neuroscience*, *14*, 3208–3224.

Shim, J., & Carlton, L. G. (1997). Perception of kinematic characteristics in the motion of lifted weight. *Journal of Motor Behavior*, *29*, 131–146.

Sloman, S. A. (1996). The empirical case for two systems of reasoning. *Psychological Bulletin*, *119*, 3–22.

Sparrow, J. T. (1999). *The blackout history project: A virtual machine that would go of itself.* Retrieved from http://sloan.stanford.edu/SloanConference/papers/sparrow.html.

Spelke, E. S., Phillips, A., & Woodward, A. L. (1995). Infants' knowledge of object motion and human action. In D. Sperber, D. Premack, & A. Premack (Eds.), *Causal cognition: A multidisciplinary debate* (pp. 44–78). Oxford: Clarendon Press.

Stanovich, K. E., & Toplak, M. E. (2012). Defining features versus incidental correlates of type 1 and type 2 processing. *Mind and Society*, *11*, 3–13.

Stanovich, K. E., & West, R. F. (2000). Individual differences in reasoning: implications for the rationality debate. *Behavioral Brain Sciences*, *23*, 645–726.

Strawson, G. (1987). Realism and causation. *The Philosophical Quarterly*, *37*, 253–277.

Straube, B., & Chatterjee, A. (2010). Space and time in perceptual causality. *Frontiers in Human Neuroscience*, *4*, 1–10.

Talmy, L. (1988). Force dynamics in language and cognition. *Cognitive Science*, *12*, 49–100.

Truman, N. E. (1904). *Maine de Biran's philosophy of will*. New York: The MacMillan Company.

Walker, P., Francis, B. J., & Walker, L. (2010). The brightness-weight illusion. *Experimental Psychology*, *57*, 462–469.

Wheat, H. E., Salo, L. M., & Goodwin, A. W. (2004). Human ability to scale and discriminate forces typical of those occurring during grasp and manipulation. *The Journal of Neuroscience*, *24*, 3394–3401.

White, P. A. (1999). Toward a causal realist account of causal understanding. *American Journal of Psychology*, *112*, 605–642.

White, P. A. (2006). The role of activity in visual impressions of causality. *Acta Psychologica*, *123*, 166–185.

White, P. A. (2009). Perception of forces exerted by objects in collision events. *Psychological Review*, *116*, 580–601.

White, P. A. (2011). Visual impressions of force exerted by one object on another when the objects do not come into contact. *Visual Cognition*, *19*, 340–366.

White, P. A. (2012a). The experience of force: the role of haptic experience of forces in visual perception of object motion and interactions, mental simulation, and motion-related judgments. *Psychological Bulletin*, *138*, 589–615.

White, P. A. (2012b). Visual impressions of causality: effects of manipulating the direction of the target object's motion in a collision event. *Visual Cognition*, *20*, 121–142.

Witt, C. (2008). Aristotelian powers. In Ruth Groff (Ed.), *Revitalizing causality: Realism about causality in philosophy and social science*.

Wolff, P. (2007). Representing causation. *Journal of Experimental Psychology: General*, *136*, 82–111.

Wolff, P., Barbey, A. K., & Hausknecht, M. (2010). For want of a nail: how absences cause events. *Journal of Experimental Psychology: General*, *139*, 191–221.

Wolff, P., Ritter, S., & Holmes, K. Causation, forces, and the sense of touch, in preparation.

Wolff, P., & Song, G. (2003). Models of causation and the semantics of causal verbs. *Cognitive Psychology*, *47*, 276–332.

Wolff, P., & Zettergren, M. (2002). A vector model of causal meaning. In W. D. Gray, & C. D. Schunn (Eds.), *Proceedings of the twenty-fourth annual conference of the cognitive science society* (pp. 944–949). Mahwah, NJ: Erlbaum.

Woodward, J. (2007). Interventionist theories of causation in psychological perspective. In A. Gopnik, & L. Schulz (Eds.), *Causal learning: Psychology, philosophy, and computation* (pp. 19–36). Oxford: Oxford University Press.