Available online at www.sciencedirect.com
ScienceDirect
Acta Psychologica 123 (2006) 144–165
acta psychologica
www.elsevier.com/locate/actpsy

The perception of causality in infancy

Rebecca Saxe [a,b,*], Susan Carey [a]

[a] *Psychology Department, Harvard University, United States*
[b] *Department of Brain and Cognitive Sciences, 46-4019 MIT, 43 Vassar Street, Cambridge, MA, 02138, United States*

Received 20 December 2005; received in revised form 29 May 2006; accepted 30 May 2006
Available online 14 August 2006

Abstract

Michotte proposed a rationalist theory of the origin of the human capacity to represent causal relations among events. He suggested that the input analyzer that underlies the causal perception in launching, entraining, and expulsion events is innate and is the ultimate source of all causal representations. We review the literature on infant causal representations, providing evidence that launching, entraining and expulsion events are interpreted causally by young infants. However, there is as of yet no good evidence that these representations are innate. Furthermore, there is considerable evidence that these representations are not the sole source of the human capacity for causal representation.

PsycINFO classification: 2820

Keywords: Cause; Infancy; Empiricism; Rationalism; Innateness; Intervention

1. Introduction

The fundamental puzzle of the origin of causal representations is that the causal connection between two events (e.g., the motions of two billiard balls, or finger movements and words appearing on a page, or rain and crop growth) seems to be something over

* Corresponding author. Address: Department of Brain and Cognitive Sciences, 46-4019 MIT, 43 Vassar Street, Cambridge, MA, 02138, United States. Tel.: +1 617 669 4856.
E-mail address: saxe@mit.edu (R. Saxe).

0001-6918/$ - see front matter
doi:10.1016/j.actpsy.2006.05.005

and above the spatio-temporal sequence of the two events. After all, night regularly follows day, but we do not perceive, or judge, that night causes day. Nor can adding statistical analyses solve this problem: two events may be described as correlated, or covariant, or conditionally dependent, without necessarily being causally related. So, how then do we come to represent some connections between covariant events as causal?

This puzzle can be divided into two parts: an epistemological one, and a psychological one. The epistemological question concerns justification: why are we justified in believing that some events in the world really are causally connected, and not just covariant? For the most part, cognitive science does not address the epistemological question, but focuses instead on an independent, psychological question: what are the basic cognitive structures in the mind that detect and label (i.e., represent) some relations between perceived events as causal? What are the inputs to these structures, and what are their outputs?

In his landmark book, The Perception of Causality (henceforth PoC), Albert Michotte proposed a detailed response to these psychological questions. A causal connection is perceived between certain pairs of motion events, he proposed, in virtue of a perceptual input analyzer that automatically and obligatorily computes a "causal impression". Michotte precisely characterised (and where possible, quantified) the visual stimulus properties necessary to produce this causal impression, and the different kinds of causal impressions that could be so produced.

Understanding the nature of any representational capacity requires an account, at least in principle, of how it might be acquired. Accordingly, although all of the data that Michotte collected consisted of verbal reports by adult observers, he nevertheless took a strong position on the origin of causal representations, in addition to their mature form. Michotte claimed that the perceptual mechanism for causal impressions was innate, and furthermore that the output of this mechanism was the source of all subsequently developing causal representations.

In 1946, Michotte formulated his developmental hypotheses without any data from children, let alone infants. "It would clearly be very interesting if experiments such as those described in this book could be tried out on children of different ages", he noted. "Unfortunately, plans for such research have not yet advanced beyond the project stage" (PoC, p. 255). Fifty years later, the empirical landscape is improving. The development of methods for studying pre-verbal infant cognition, based on the infants' looking-times at different categories of events, has provided unprecedented access to the earliest stages of cognitive development. Interest in the earliest causal representations, in particular, is growing rapidly.

In the current paper, we evaluate three interrelated Michottean claims about the perception of causality by young infants: first, that the perception of causality in launching and entraining events is very early-developing (Section 2); second, that the perception of causality in these events depends on strictly limited aspects of the input, and is not easily infiltrated by other information (Section 3); and third, that perceived causality in other domains is generalised from the developmentally and conceptually prior representation of causality in motion events like launching and entraining (Section 4). To anticipate briefly, we conclude that evidence from infancy provides support for the first of these claims but substantially undermines the second. Although the evidence is not yet definitive, the available data are also inconsistent with the third claim: namely, that the causal impression received from motion events is the original idea of causality.

2. Background: Theories of the origin of causal representations

Michotte contrasted his own theory of perceived causality most directly with an extreme empiricist approach that he attributed to the philosopher, David Hume.[1] Empiricist theories start by positing lean primitive representational resources (sensations, and the spatio-temporal relations among them), and seek to show how representations of causal interactions are built from those primitives alone. Michotte took the reduction of causal notions to spatio-temporal and phenomenal features to be a reasonable response to the epistemological question about causal representations, but not to the psychological question of what underlies the impression of causality: "We are then [in response to the epistemological question] trying to understand what is 'really' happening in 'the external world'. [···] Analytical observation clearly allows us to recognise only a succession of movements. [···] Even though this mode of observation was the most suitable to give an accurate account of physical facts, it had the result of splitting the phenomenal world into pieces and making the most interesting psychological facts disappear" (PoC, p. 8).

These most interesting psychological facts are the data showing that "certain physical events give an immediate causal impression, and that one can 'see' an object act on another object, produce in it certain changes, and modify it in one way or another" (PoC, p. 15). One example is the pattern that Michotte named "launching": Object A approaches and contacts Object B, and then immediately afterwards Object B goes into motion. Using the reports of trained observers, Michotte studied minutely the stimulus properties necessary to produce an impression of causality in this kind of sequence. In a fascinating set of experiments, he showed that launching is perceived when and only when the two motions have parameters consistent with a single motion transferred from one object to a second, perceptually distinct one.

Based on his experimental results, Michotte proposed the existence of a special mechanism in the mind that transforms privileged inputs—visual sequences of motions with certain spatio-temporal parameters—into a "genuine causal impression." This mechanism exhibited the hallmarks of a perceptual process, rather than a conceptually mediated inference. The perception of causality in these events is fast and automatic, and subjects do not have introspective access to intermediate stages of the computation. Nor does the causal impression reflect the subjects' explicit causal beliefs. Only a strictly limited set of stimulus properties influences the perception of causality. Even when the observers knew that a genuine causal interaction was impossible, because the two moving objects were lights on a wall or marks on paper, the impression of causality was not reduced. Furthermore, the precise stimulus properties that do produce a causal impression correspond neither to the properties of real causal interactions in our friction-full Newtonian world, nor to our lay theory of mechanics. This aspect of Michotte's theorizing leads some modern writers to note that Michotte anticipated Fodor (1983) in characterizing the mechanism of perceptual causality as modular (fast, automatic, data driven from limited and privileged input, and encapsulated from explicitly held knowledge; see Scholl & Tremoulet, 2000).

[1] Most commentators on Hume do not read him in this way—Hume thought that a "causal sense" is innate and that causality is projected onto the world by the mind, just as are moral judgments and aesthetic judgments (see Garrett, 2006, for example). However, modern thinkers such as Leslie Cohen (e.g., Cohen, Amsel, Redford, & Casasola, 1998; Cohen & Chaput, 2002) espouse the empiricist position attributed by Michotte to Hume.

By contrast with his empiricist reading of Hume, Michotte was thus a rationalist: he believed that causal representations are innate, and that their developmental source is the input analyzer that underlies the perception of physical causality, for example in launching. One critical challenge for this view is that in adulthood, the perception of causality in motion events undeniably co-exists with other forms of causal inference that do not proceed via a perceptual input analyzer, but nevertheless invoke causal representations. Michotte explained that "there are many cases where a causal interpretation must be the result of an elaboration, by means of reflection, on the data of experience. This is true, for instance, of the relation between the sowing of a field and the later appearance of the crop, or the heating of water and its starting to boil; and, in the sphere of mechanics, it is true as an explanation of occurrences such as the negative cases mentioned earlier—the obstruction of a moving object by an obstacle, braking, attraction, rebounding, and so on. Since causality is not 'given' in these cases, the idea of it cannot be derived directly from the 'experiences' in question. Thus, the claim that causality is intervening must rest on an inference, an inference which itself presupposes the existence of an original idea of cause" (PoC, p. 257). This original idea of cause, argued Michotte, was precisely that received through the operation of the perceptual input analyzer.

In his own experiments, Michotte identified temporally contiguous pairs of events that are not automatically or obligatorily perceived as causally connected: for example, when Object A moves until it contacts Object B, and Object B then changes colour. Michotte called this an example of "qualitative causality". For any extension of causal inference to such events "the first [requirement] is that there should be [a perceptual] impression of causality or mechanical activity; the second is that the qualitative event should be integrated in this impression" (PoC, p. 257). That is, observers can infer a causal connection between non-motion events by generalising from the developmentally and conceptually prior perceptual causal impression.

Of course, this is not the only possible rationalist theory for the origin of causal representations. Michotte himself recognised at least one alternative, represented by the philosopher Maine de Biran (and to a lesser extent, by Piaget): that the innate source of all causal representations lies in our experience of being causal agents. According to de Biran, "A being who has never made an effort would not in fact have any idea of power, nor, as a result, any idea of efficient cause. He would see one movement succeed another, e.g., one billiard ball hump into another and push it along; but he would be unable to conceive, or apply to this sequence of movements, the idea of efficient cause or acting force, which we regard as necessary if the series is to begin and continue." (quoted in PoC, p. 11). On de Biran's theory, the privileged input to a causal representation is a sense of one's own agency and a sensation of one's own physical effort. The causal schema of the output is that of a causal agent effecting changes in the world through the action of internally generated force.

White (2006) endorses a view that is a modern version of de Biran's. White's starting point is a striking fact about causal representations: they are asymmetric in a way that mechanical interactions in the world are not. Take Michotte's launching events, for example. While it is true that A's hitting B causes B to move, it is equally true that B's being hit causes A to stop. Yet, in thousands of experiments eliciting descriptions of launching events, participants virtually never report seeing B make A stop moving. White suggests that this asymmetry is a remnant of the original developmental source of causal

representations—the child's own action on the world, her experience of internally generated force and her experience of the effects of her actions including the felt resistance of the objects acted upon. White offers no developmental data in support of his position, but we suspect he will find comfort in some of the data presented below.

Both Michotte's proposal and Maine de Biran's posit innate representations of cause. They differ in what are taken to be the earliest, most basic inputs used to identify causal interactions in the world, from which the full rich adult application of the concept must be generalised or derived. By direct contrast with de Biran, Michotte claimed that even the experience of internal causation, within the mind of the experiencing agent, is derivative: "The qualitative event—the emotion or motivational state—often precedes a physical action, e.g., of pulling something towards ourselves, taking it up, pushing it away, and so on, and is closely linked with the corresponding causal impression. Here, surely, is to be found the basic reason why people attribute a causal role to emotions or sentiments, some of which perhaps possess in themselves a character of immanent activity, but not of causality in the strict sense" (PoC, p. 260). Michotte concludes "that the causal impression in the strict sense [that is, based on the perceptual input analyzer] forms the basis on which the clearly defined idea of cause is founded, and that, once acquired, this idea can be applied [to one's own voluntary action] as a result of the qualitative likeness between the phenomena" (PoC, p. 271).

A third, distinct rationalist theory of the origin of cause was not recognised by Michotte. A modern descendent of Hume's theory posits a cognitive mechanism that identifies causal interactions based on covariation and conditional dependence data. This theory differs from both Michotte and de Biran in proposing that the basic causal representations are not restricted to a single domain (like visually perceived launching, or internally experienced agency) but are rather defined over any pair of experiences. Many modern cognitive scientists propose models along these lines that learn particular causal relations among events in the world from evidence of conditional probabilities (see, for example, Cheng & Novick, 1990; Dickinson & Shanks, 1995; Gopnik et al., 2004; Pearl, 2000). These models posit no constraints on the kinds of events that might be related causally. Still, their authors propose that the capacity to represent relations as causal is not itself learned from experience, but is rather an intrinsic feature of the cognitive mechanism. On this view, the privileged input is a representation of conditional probabilities and the causal schema is something like a directed causal graph that supports counterfactual reasoning and interventions on the world.

In the current paper, we do not address the empiricist–rationalist debate empirically. Rather, we accept Michotte's (and Hume's) logical arguments that one cannot learn about causes without the prior capacity to represent some experiences causally. Nor will we be directly concerned with the question of whether the perception of causality is modular in adults (for a discussion of the data from adults and children, see Choi & Scholl, 2004, 2006; Schlottmann, 2000; Schlottmann, Allen, Linderoth, & Hesketh, 2002, 2006; Schlottmann & Shanks, 1992; Schlottmann, Surian, & Ray, submitted for publication; Scholl & Tremoulet, 2000). Our present concern is how Michotte's theory of the origin of causal representations stands up to recent evidence from infancy. We examine three interrelated claims derived from Michotte's proposal. First, the perception of motion events as causal should emerge early in development. Second, infants' earliest causal representations should depend solely upon the highly restricted, privileged input to Michotte's perceptual mechanism, and should not be influenced by other causal knowledge.

Finally, the causal impression derived from this mechanism should be developmentally prior to causal representation of other, non-motion events.

3. Early perception of motion events as causal

Modern research on infants' conceptual and perceptual capacities draws upon patterns of looking times to diagnose their mental capacities. The basic idea is straightforward. Besides testing what stimulus features infants can discriminate, these experiments often test violation of expectancy. Infants' attention is drawn to the unexpected, and thus patterns of attention provide information concerning the representations that underlie the expectations (see Spelke, 1985, for an overview of this method).

Looking time experiments may provide two kinds of evidence that infants perceive an event as causal. The first is evidence that infants are sensitive to the same properties of the input that determine the perception of causality in adults, such as spatial and temporal contiguity of the two motions. The second is evidence that infants' representations of events go beyond generalizations stated in a perceptual or spatio-temporal vocabulary.

For at least one class of motion events—namely, launching events—very young infants certainly are sensitive to spatial and temporal contiguity between the two motions. The simplest experiments exploring infants' representations of launching events begin by letting infants watch an event in which B goes into motion immediately upon being contacted by A. After habituation, infants are shown either more launching events, or events in which there was a temporal delay or a spatial gap. Events with spatial or temporal gaps retain the basic sequence of one event followed by another, but do not yield a perceptual experience of causality in adults. The question is: by what age do infants detect the difference? As young as 4 months, infants successfully make this discrimination, expressed by regaining interest (increasing looking time) to the spatial or temporal gap events (Cohen et al., 1998; Leslie, 1982, 1984b). Of course, this result merely shows that infants are sensitive to contact in sequences of motion events; it does not yet establish that infants are representing those events as causal.

A study by Kotovsky and Baillargeon (2000) (illustrated schematically in Fig. 1) goes a bit further. Instead of habituation, 7.5-month-old infants are simply familiarised to the apparatus: a ramp (the path for Object A), Object B lying stationary near the bottom of the ramp, and between them a barrier which either completely blocks access from the ramp to B, or has a gap. The bottom half of the barrier and the near end of B are then occluded by a screen, and infants see Object A placed at the top of the ramp and released, and then roll down the ramp and disappear behind the screen. Object B then moves across the stage, in a manner consistent with launching by Object A. Infants show increased looking (i.e., surprise) when Object B moves in the full-barrier case, when contact between Objects A and B behind the screen is not possible. A second group of infants see the same sequence of events with one change: Object B does not go into motion after Object A disappears behind the occluder. In this case, infants look longer at the opposite event, when contact is possible, than when contact is not possible. Kotovsky and Baillargeon's data thus suggest that infants can use the possibility of spatial contact between A and B to form expectations about Object B's subsequent motion.

A third set of experiments suggest that infants can also run this inference in reverse, using the relations between of Object B's and Object A's motions to infer spatial contact between the two objects, even if they have no visual evidence concerning the exact

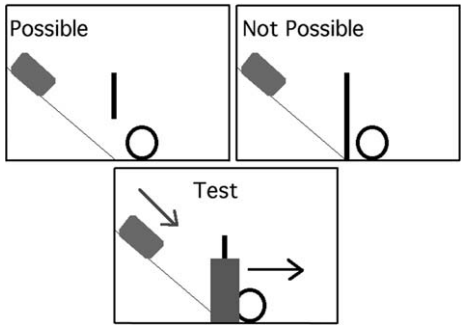

Fig. 1. Illustration of the paradigm used by Kotovsky and Baillargeon (2000). One group of infants was familiarised to the initial display shown in (possible, left): an object at the top of the ramp (Object A), an inanimate object lying at the bottom of the ramp (Object B), and between them a barrier. For the first group, the barrier had a gap so that contact between the two objects was possible. A second group of infants saw the initial display shown in (not possible, right), with the barrier completely blocking contact between the two objects. Both groups then saw the same test trial. The bottom of the barrier was occluded. Object A was released at the top of the ramp. After the leading edge of A disappeared behind the occluder, Object B began to move across the stage. Infants who had seen the "Not Possible" familiarisation display looked longer at the test trial than did infants who had seen the "Possible" display.

interaction. The basic paradigm is that used by Ball (1973) in the study that introduced the violation of expectancy looking time methodology to the field of infant research. In Ball's original experiment (see Fig. 2 for a schematic of Ball's design) 6–26-month-old infants are shown an event that begins with a screen visible on a stage floor with an object, B, partially visible at its right edge. A second object, A, rolls onto the stage from the left and continues rolling until it disappears behind the screen. After timing consistent with a launching event, Object B goes into motion and stops, visible, to the right of the screen. The infants see this event over and over, until they have encoded it fully enough to become habituated to it. They are then shown two test events, in alternation, only one of which is unexpected

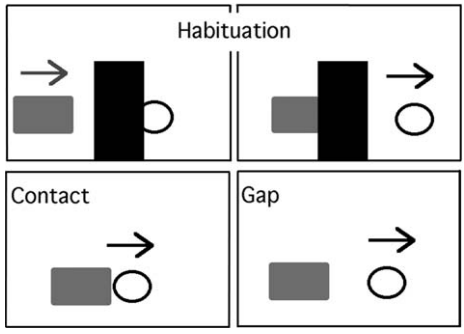

Fig. 2. Illustration of the paradigm introduced by Ball (1973). In the habituation trials, a screen occludes the centre of the stage/image, and the left edge of Object B. Object A moves across the stage until its right edge disappears behind the screen, and then stops. Object B then immediately starts moving across the stage. During the test trials, the occluding screen is then removed. Infants see the whole interaction unfold. In 'Contact' trials, Object A contacts Object B, consistent with launching. In 'Gap' trials, there is a spatial gap between Object A's final position and Object B. Infants look longer at the event with a spatial gap. This paradigm has been adapted by many other researchers to study infants' expectations of contact.

if the infants represent this ambiguous event as launching. The screen is removed, and the sequence of A's motion and then B's motion happens as before. 'Contact' test trials fulfilled the conditions for a launching event, including no gap between Object A's final position, and Object B's starting position. On 'non-contact' test trials, a spatial gap between the two objects was introduced, interfering with the perception of launching. Infants look longer at non-contact trials. The same result has since been replicated separately with 9-month-olds (Kosugi, Ishida, & Fujita, 2003), 8-month-olds (Muentener & Carey, 2006a), and 6-month-olds (Spelke, Phillips, & Woodward, 1995).

In Michotte's experiments spatial contact between the two objects is a critical feature of events perceived as causal. Evidence that infants form expectations about contact in apparent launching events thus supports Michotte's claim that the perception of causality in launching events is continuous between infants and adults. Nevertheless, these data may require a friendly amendment to the perceptual input analyzer proposed by Michotte, to allow the perception of a causal interaction that persists over occlusion, making the contact between the objects invisible. That is, the perceptual input analyzer would have to operate over the *perceived* stimulus, rather than the visible images (for evidence that Michotte was amenable to this distinction between the visible stimulus and the perceived stimulus, see the amodal completion phenomena discussed in this issue, e.g., Bertamini & Hulleman, 2006; Fulvio & Singh, 2006; Kawachi & Gyoba, 2006).

Altogether, these results show that infants are sensitive to some of the spatio-temporal parameters that determine the adult perception of launching, and can use these parameters to predict when motion should occur. Still, the challenge for researchers remains to show that infants perceive these events in terms of *caused* motion (rather than merely predicted motion). One approach to this challenge is to show that infants categorize different spatio-temporal patterns together on the basis of whether they specify a causal interaction or not. For example, Oakes and Cohen (1990) habituated babies to launching events or to events that are seen by adults as non-causal for one of two reasons—either because there was a period of time after contact by A before B stated to move or because A stopped short of B before B went into motion. The habituated event was then contrasted with each other event. In the first studies of this kind, 10-month-old generalized habituation from one non-causal event to another while dishabituating from either non-causal event to the causal one. That is, for these infants, physically identical spatio-temporal differences between events are not perceptually equally salient; the properties that produce a causal impression in adults are perceptually distinct for infants, too. This experiment suggests that the infants categorically distinguish causal from non-causal interactions. Further experiments brought the age of categorical distinction down to 7 months.

The second line of evidence that infants' representations of launching events go beyond spatio-temporal generalisations comes from evidence that infants assign distinct roles to the agent and the recipient in launching events, but fail to do so for pairs of events that follow each other regularly without a causal interaction. Within a single causal interaction, two entities play complementary roles: we will call these roles 'agentive' and 'receptive' roles, respectively. For example, in an archetypal causal sequence a hand moves a billiard cue, which hits the white ball, which rolls across the table to hit the red ball. The white ball plays the receptive role in one specific causal interaction (with respective to the agentive stick), and then the agentive role in the subsequent interaction (with respect to the receptive red ball). This distinction between roles in a causal interaction goes beyond just the temporal order between the two motions.

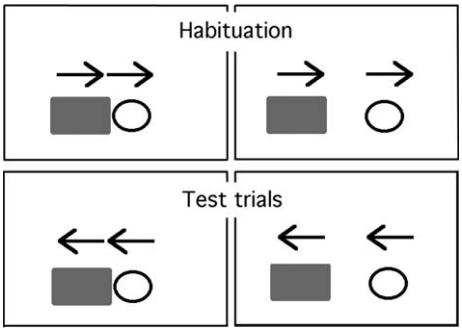

Fig. 3. Illustration of the paradigm used by Leslie and Keeble (1987). Infants are habituated (top panels) to a sequence of Object A's motion, followed by Object B's motion. Half of the infants see a "launching" event; the other half see the same sequence but interrupted by a gap between A and B. At test (bottom panels), the same movies were played backwards. Infants dishabituated to the reversal only if they had seen "launching" (no gap) during habituation.

Leslie and Keeble (1987) (illustrated schematically in Fig. 3) habituated one group of infants to launching events; a second group was habituated to nearly identical events, but with a temporal delay introduced between the two motions. In spatio-temporal terms, both events could be described as Object A moves, and then Object B moves. However, as described above, adults distinguish the agent and patient of the causal interaction ("A *causes* B to move"). Leslie and Keeble then showed infants the same events, but in reverse temporal order. Reversing a non-causal event changes only the order of the two motions (now "B moves and then A moves"), but reversing an event perceived causally also switches the roles of the two objects (now "B *causes* A to move"). This is what happened: 6-month-old infants do not regain interest when the temporal-gap event is played in reverse temporal order, but they do regain interest when the launching event is reversed. The authors conclude that infants' representations of launching events go beyond a spatio-temporal generalisation.

Suppose we accept, for the sake of argument, that the above studies establish that infants as young as 6 months of age perceive causality in launching just as do adults (and we provide more evidence in favour of this interpretation below). This conclusion is certainly consistent with Michotte's claims concerning the developmental priority of causal perception in the ontogeny of causal representations. Still, these findings fall far short of proving Michotte's hypothesis that the perception of causality in motion events is the root of the human capacity to represent *cause*. In the next section, we describe evidence that infants' causal perceptions are not restricted to the perceptual mechanism's privileged input, but are influenced by multiple distinct sources of causal information.

4. Early integration of information from distinct sources of causal representation

The Michottean developmental hypothesis predicts that infants' earliest causal representations are not sensitive to information that goes beyond the hypothesized privileged input to the input analyzer. Evidence that infants *are* sensitive to such information would thus require one of two amendments: either the mechanism for the perception of causality

is itself sensitive (at least in infants) to additional information, beyond the privileged spatio-temporal parameters that Michotte identified, or infants' earliest causal representations depend on mechanisms other than the perceptual input analyzer, including information integrated from higher-level cognitive inferences. Both Michotte and the researchers who have followed him provide substantial evidence that for adults, the causal impression produced by a launching event depends on the spatio-temporal properties of the two entities' motions, but is not influenced by any intrinsic properties of the entities themselves. Michotte concluded that "the causal impression which appears in the Launching Effect is independent in principle [···] of the phenomenal aspect of the objects" (PoC, p. 85)—namely, their size, shape, colour and constitution. A causal impression could even be evoked by the right sequence of motions involving a wooden ball (Object A) and a circle of light (Object B, PoC Experiment 28). Michotte stressed the importance of this result for understanding the mechanism of causal perception: "The causal impression persists even in the face of direct opposition from the facts of paste experience. We know perfectly well that a 'real' ball cannot 'drive away' or 'launch' a reflected image or a show. It is in defiance of this knowledge that we actually *see* the launching of one by the other" (PoC, p. 85).

If the "original idea of cause" is the output of this perceptual mechanism, then at the earliest ages when infants perceive causal impressions of launching, their causal perceptions should be similarly blind to the nature of the entities in the interaction. It is simply not so. Stimulus variables other than direction of and priority of motion and the spatio-temporal parameters of the interaction influence infants' representations, at the same age as infants first represent launching events as causal at all. Below, we discuss evidence for influence on infants' earliest causal representations of motion events from three sources: information about the relative sizes of objects; information about the dispositional causal status of the object in the recipient role (Object B); and information about the dispositional causal status of the object in the agentive role (Object A).

4.1. The relative sizes of objects

Michotte found that the perception of launching "is largely independent of the shape, size, and colour of the object" (PoC, p. 83, but see also Runeson, Juslin, & Olsson, 2000). By contrast, in an elegant study Kotovsky and Baillargeon (1998) (Fig. 4) showed that 5.5 and 6.5-month-old infants already use the intrinsic feature of object size to formulate expectations about launching events. The infants were habituated to a simple launching event, in which a medium sized cylinder rolled down a hill until it contacted a stationary "bug" at the bottom of the hill; the bug then moved to the middle of the stage (so the event was perceived by adults as the cylinder launching the bug). For the test trials, the medium cylinder was replaced by either a small cylinder or a large cylinder. After being struck by the new test cylinder, the bug always moved to the far end of the stage, significantly farther than it moved during habituation. The 6.5-month-old infants in this experiment looked longer on the trials involving the small cylinder than the large cylinder, suggesting that infants' expectations about the motion of the recipient object in a launch event depend on the *size* of the active object (all things being equal, smaller objects should cause smaller motions, not larger ones). In particular, infants were sensitive to the sizes of the active objects during test relative to the habituation event, and to the relative motions those objects could be expected to cause by launching the recipient object. Kotovsky and

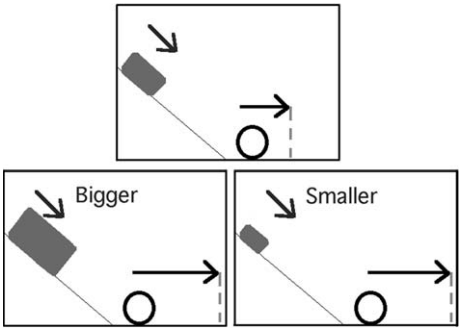

Fig. 4. Illustration of the paradigm used by Kotovsky and Baillargeon (1998). During habituation (top panel) infants saw a medium size cylinder roll down a ramp and launch the Object B at the bottom, which then rolled half way across the stage. For the test trials (bottom panels), the cylinder was replaced by either a bigger, or a smaller, cylinder. On all trials, Object B rolled all the way across the stage. Infants looked longer at the test trials using the smaller cylinder than at those using the bigger cylinder.

Baillargeon took these results as evidence that the infants integrate information about an intrinsic property of the active entity (namely, its size) into their representation of launching events, and we agree.

The results for the younger infants were even more striking. Female 5.5-month-old showed the same pattern of looking as did the older infants. The male 5.5-month-old, on the other hand, did not dishabituate in response to either test trial condition. To make sure that the younger males did remember the habituation events, and could detect a change in the motion of the bug at test, Kotovsky and Baillargeon (1998) introduced a new pair of test trials for just the younger male infants. The habituation was the same as before (medium cylinder causes medium motion), but at test the cylinder changed colour, and the bug rolled all the way to the end of the stage. In this case, the young males *did* dishabituate. Taken together, these results suggest that even 5.5-month-old boys expect that the size, but not the colour, of the agentive object can make a difference for the subsequent motion of the recipient object. They simply have not fully worked out exactly how size should make a difference.

Overall, these data bolster our confidence that infants are indeed reasoning causally, as Michotte would want, because infants' expectations about launching events are influenced specifically by causally relevant variables (size, not colour). But for the Michottean hypothesis described above, this result is a double-edge sword, because it also means that, unlike the perceptual mechanism Michotte identified in adults, infant's earliest causal representations are influenced by at least one intrinsic property of the objects: size. Of particular importance is the age of the children—5- and 6-month-old. They are roughly the same age (indeed even younger) as the youngest children to give unambiguous evidence for causal interpretations of launching at all in the Leslie and Keeble (1987) and Oakes (1994) experiments. Further studies would of course be useful, in order to test whether infants in this experiment were responding based on the object's size (another visual property of the event) or weight (information in the domain of Maine de Biran's hypothesis about the causal primacy of experienced effort).

4.2. The nature of the entity in the receptive role influences causal representations

Michotte recognized that some entities are perceived as self-moving, and studied some of the stimulus parameters that led viewers to perceive a motion as internally caused. Young infants similarly distinguish animate motion from linear, smooth, rigid motion (Berthenthal, 1993), and attribute goals, attentional states, and social causality to entities as a function of how they interact, even if the entities do not have the morphological features of typical animate agents (Gergely, Nadasdy, Csibra, & Biro, 1995; Johnson, Slaughter, & Carey, 1998). None of this work undermines Michotte's developmental claims concerning physical causality. What *is* problematic for his claims is a large body of recent work showing that, in addition to perceiving physical causality in motion events, very young infants track the ontological status and stable causal dispositions of the participants in *physical* causal interactions (i.e., launching, entraining and expulsion events), and use this information to inform their interpretation of the causal interaction itself.

Research on infants' inferences about the participants in a physical causal interaction can thus be divided into two streams: studies investigating infants' expectations about the 'receptive' role, and those investigating expectations about the 'agentive' role. Many studies now establish that infants' inferences about partially occluded launching events, like those used by Ball (1973) described above, depend critically on the ontological status of the entity the infant sees in the 'receptive' role. The results described above—longer looking at 'non-contact' than 'contact' test trials—applies only when the entity in the receptive role is an inert inanimate object. Spelke et al. (1995) showed infants the same events as in Ball (1973), but in which Objects A and B were human beings. Six-month-old infants in the new People version did not differentiate 'contact' and 'non-contact' test trials; a person going into motion without having been contacted by another person did not draw more attention than a person going into motion after having been contacted by another moving person. Kosugi and Fujita (2002) replicated and extended this finding. Infants did not look longer at 'non-contact' test trials. In these studies, infants' inferences draw on information that transcends the restricted vocabulary of Michottean input, and at the earliest age (6 and 7 months) at which there is good evidence that launching is perceived as such.

The dispositional status of the object in the receptive role has a particularly important and clear effect when infants make inferences about no-contact events. When an event fulfils the spatio-temporal criteria for launching and is fully visible, a perceptual input analyzer produces a "causal impression"—independent of the identities of the interacting objects. But what if the event does not fit the criteria for launching, because of a spatial gap or obstacle? Kotovsky and Baillargeon (2000) argue that 7.5-month-olds' response to no-contact events depends on their prior categorisation of the object in the receptive role. Their claim depends on a contrast between their study, described above, and a range of other studies in the literature. Remember that in Kotovsky and Baillargeon's paradigm, infants looked longer at the very first trial in which Object A's motion was followed by Object B's motion if contact between the two objects was not possible. Many previous studies, though, report that infants do not look longer at "launching" events with a spatial gap unless they have had habituation trials (Kosugi et al., 2003; Leslie, 1984b; Oakes & Cohen, 1990). Kotovsky and Baillargeon (2000) suggest that the critical difference between the studies is whether infants characterise Object B as dispositionally inert or as self-moving. In experiments that use unfamiliar objects presented on a video screen and a self-moving novel

Object A, there is no reason for infants to initially categorise Object B as either self-moving or inert, so neither categorisation is inherently surprising. If Object B is categorised as self-moving, then motion of Object B can occur even if there is a spatial gap between the two objects. By contrast, Kotovsky and Baillargeon (2000) encouraged infants to categorise their Object B as inert, by using real objects presented on a stage, by familiarising infants with Object B lying stationary on the stage, and by using a dispositionally inert Object A. The critical features of this experiment are that (a) infants have evidence to classify Object B as dispositionally inert, but (b) there are no habituation trials. Nevertheless, infants show increased looking (i.e., surprise) when Object B moved only in the full-barrier case, when contact is not possible, and not if contact is possible. That is, if (and only if) the entity in the receptive role is categorised in advance an inanimate and inert, then infants look longer at an apparent no-contact event even on the very first trial. Kotovsky and Baillargeon (2000) also describe unpublished results showing that 6-month-old infants are surprised if an object categorised as inert does not move when contact *is* possible, but are not surprised by this event if the recipient was previously categorised as self-moving.

These experiments suggest that from the earliest age that infants represent *physical* causality, their reasoning is deeply conditioned by the remembered dispositional status of Object B. Again, these results highlight the dissociation between the output of the hypothesized data driven perceptual input analyzer—which detects the spatio-temporal profile of launching independent of the ontological status and stable causal dispositions of the interacting entities—and the overall behaviour of the infant—which includes inferences based on that status.

4.3. The nature of the entity in the agentive role influences causal interpretation

A distinct set of experiments investigates the interactions between infants' causal inferences and the nature of the object in the agentive role. Again, simple but powerful paradigms have been developed using events that do not fit the specifications of "genuine" perceptual causality: in this case, motion events in which the causal structure is ambiguous, not specified by spatio-temporal cues. For example, Pauen and Trauble (submitted for publication) let 7-month-old infants watch an ambiguous motion event, in which a ball attached to a furry animal-like tail bounced and rolled erratically around a small stage. Since both the ball and the tail always moved together, causal roles could not be assigned based on spatio-temporal cues. Then, the ball and the tail were separated, and lay stationary in separate parts of the stage. Although the infants' exposure to the two objects (ball and tail) moving was equivalent and ambiguous, and infants showed no baseline preference for either object, the looking behaviour to the stationary objects after the exposure to their joint motion was asymmetrical. Infants looked preferentially at the tail, as if they expected the tail, but not the ball, to continue to move following separation.

Pauen and Trauble's data suggest that when two entities moved together, 7-month-old infants parsed the spatio-temporally ambiguous motion event into a causal interaction based on cues to dispositional agency. The infants assigned the furry tail (a more plausible agent in the enduring, dispositional sense) to the agentive role—just as adults do with the same stimuli. Notice that this event exemplifies entraining, not launching, although it does not provide Michotte's evidence concerning the respective roles in an entraining event. The infants are never shown A in motion, B at rest, A contacting B and entraining it. Still, the fact that infants are sensitive to the stable dispositional properties of A and B in predicting

further motion suggests that they interpreted the motion of the ball (B) as caused by the motion of the tail (A). Pauen and Trauble thus provide evidence that in addition to launching, 7-month-old infants interpret entraining causally.

Work in our own lab (Bhojani, 2006, illustrated in Fig. 5) replicates Pauen and Trauble's basic finding, supports their interpretation, and provides further evidence that infants see entraining causally. Seven-month-old infants watched a live human hand and a novel cylindrical, brightly coloured object moving back and forth in front of a stage. When the curtains opened, the objects were already in motion. The infants in the 'contact' condition saw the hand and object touching throughout the motion. Importantly, there were no cues to the support relation between them (which were in fact both supported independently) and no spatial or temporal cues to distinguish the agentive and receptive roles. The infants in the 'no-contact' condition saw the same events with a rigid spatial gap between the hand and the object. In both cases, the hand's motion and the novel object's motion were identical, and perfectly contingent on one another. Then on each test trial, infants saw either the hand, or the novel object, moving alone while the other remained stationary.

In this paradigm, the spatio-temporal cues that distinguish the agentive and receptive roles in Michotte's entraining events were entirely absent. Nevertheless, infants appeared to recognise the "contact" event, and not the "no-contact" event, as a causal interaction. Infants in the "contact" condition looked longer at Object-moving test trials than at Hand-moving test trials, while infants in the "no-contact" condition did not discriminate between these two test trials. We interpret these results as evidence that the infants understood the "contact" condition as a causal interaction, so the motion of the novel object was interpreted as entrained by the motion of the hand, and the novel object was categorised as inert. Consequently, infants were surprised when the inert object moved independently on the test trials. On the other hand, the spatial gap in the "no-contact" condition forced infants to interpret the novel object as self-moving, and so these infants were not surprised when the novel object moved independently on test trials (Bhojani, 2006).

With respect to infants' representations of entraining, sensitivity to the contact between the hand and novel object together with sensitivity to the status of a hand as a dispositional

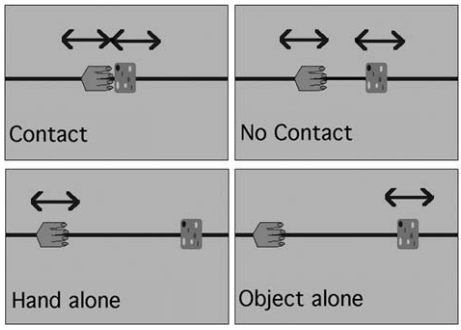

Fig. 5. Illustration of the paradigm used by Bhojani (2006). During habituation (top panels), one group of infants saw a hand and a novel object moving together back and forth in spatial contact. A second group of infants saw the same event, with a spatial gap ("no contact") between the two objects. All infants saw the same test trials (bottom panels). On alternating trials, either the hand moved alone or the object moved alone. Infants looked longer at the novel object moving alone only if they had seen the "contact" habituation.

agent suggest that they were interpreting the entraining event causally. These data are thus consistent with Michotte's predictions of early representations of entraining. Inconsistent with his predictions, though, representations drawn from memory of Object A's dispositional status as a self-moving agent organize the infant's causal interpretation.

These recent results thus converge with those of the classic study of infants' perception of causal agency by Leslie (1984a). In that experiment, 6.5-month-old infants watch a film of a hand either (1) move in from off-screen and stop near a stationary doll (Reach), or (2) start near the stationary doll, and then move off-screen together with the doll (Pick-up). In addition, each film involves either (a) contact, in which the hand contacted the doll, or (b) no contact between the hand and the doll. Leslie observed that the infants who are habituated to a Pick-up event recover interest on the test trials if the contact relation changes (from contact to no-contact, or vice versa); the infants do not respond to a contact change in a Reach event. When an inanimate object is the candidate agent instead of a hand, infants do not recover interest to a contact change for either Pick-up or Reach events. Taken together, these results suggest that 7-month-old see an event in which a hand and an inanimate object move together as a causal interaction, and they attend to contact relations between the hand and the object. An event in which two inanimate objects move together equivalently is not perceived as a causal interaction by this measure. So as in the previously described studies, infants' causal interpretation of physical motion events is conditioned on the dispositional status of the candidate agent of the entraining interaction—hands entrain, sticks do not.

Further work in our lab has shown that the young infants' inferences about the agent in a causal interaction are impressively sophisticated. Consider the following situation: two boxes are on a stage and a beanbag comes flying out of one box, landing between the two boxes. The curtain closes, opens again to reveal the two boxes, and again, a beanbag comes flying out of the same box, landing in the middle. Infants are habituated to this event. The question is do they reason about the (invisible) source of the beanbag's motion? In a series of experiments, we have shown that 7- and 10-month-old infants do reason about the source. If they have had previous evidence that the beanbag is an inert object, they infer a hidden causal agent (e.g., a human hand) as the source of the motion (inside the box), and are surprised if an inert object is revealed in the source position instead (Saxe, Tzelnic, & Carey, in press).

Note that information about the ontological categories of the entities is actually playing two different, and critical, roles in these inferences. First, infants categorise the moving entity (the beanbag) as inert, and therefore seek an external causal explanation of the beanbag's motion. If the moving object is categorised as self-moving, then infants do not seek an external cause (Saxe, Tenenbaum, & Carey, 2005). Second, infants categorise the potential causal agents, and judge that a human hand is a more likely causal agent than is an inert toy train.

The overall message of these studies is that 6–7 month old infants already form expectations with causal content that cannot be described in terms of the restricted vocabulary of Michotte's input analyzer. Their inferences rely on the categorisation of the entities in the receptive and agentive roles in terms of enduring causal dispositional status. Thus, these results clearly weigh against the Michottean contentions that (1) the early perception of causality in motion events is restricted to spatio-temporal features of the objects' motions and their interactions, or (2) that it is the single origin of all true causal concepts.

5. Are causal representations limited to motion events in infancy?

According to Michotte's theory, not only are the inputs to the mechanism for perceptual causality sharply restricted, so too is the catalog of possible causal perceptions. He offered experimental evidence that observers did not perceive a qualitative change as causal (as when Object B changes color immediately upon being contacted by A). He claimed that other qualitative changes, such as Object B collapsing or expanding upon being contacted by A, were perceived as causal only insofar as the state change could be seen as an ampliation of the motion of A (though for an argument against this restriction, see White, 2006; White & Milne, 1997, 1999). The question arises, then, whether infants' representations of cause are limited to launching, entraining, and expulsion events in which the motion of one whole object is caused by the motion of another. Evidence that infants represent qualitative changes causally would further undermine Michotte's hypothesis that representations of launching and entraining are the sole source of the human capacity for causal reasoning.

In our lab, Paul Muentener has just begun to explore this issue, and his first results tell a clear, if preliminary, story. Muentener began by replicating Ball's result with 8-month-old children. In his version, a box was partially visible behind a screen. A train rolled in from off stage, passing behind the screen, after which the box went into motion. After habituation to this event, the screen was removed and the event repeated. On alternating test trials the box went into motion upon having been contacted by the train (contact event) or the train stopped short of the box, at which time the box went into motion (spatial gap event). Just as in Ball's study, infants looked longer at the gap event.

Muentener then repeated this experiment in two new conditions involving state changes, each with new samples of 8-month-old infants. One involved a color/sound state change; the train went behind the screen, after which the box changed color and played a short tune. The other was a collapse; the train went behind the screen, after which the box collapsed into six separate pieces (illustrated schematically in Fig. 6). After habituation, the screen was removed, and infants were shown test trials which consisted of events in which the state change occurred immediately upon the box's being contacted by the train (contact event) or immediately upon the train's stopping short of the box (gap event). Infants utterly failed to differentiate the contact events from the gap events in the test trials (Muentener & Carey, 2006b). Just as Michotte would predict, infants failed to represent a state change causally under closely matched conditions to those in which they represented launching causally.

There is, however, an alternative interpretation of Muentener's data. Perhaps infants did perceive the state change events causally, but did not consider contact to be necessary for causal interactions that do not involve ampliation of motion. Muentener's next studies ruled out that possibility, and showed that infants of this age *do* expect contact in qualitative causal interactions, but just do not recognize the train sequences as causal. He repeated these studies, replacing the train with a human hand—a paradigm dispositional agent, as we have seen in Section 4. As before, the curtain to the stage opened, revealing the box, half hidden behind a screen. On habituation trials, an arm with the index finger of the hand pointing forward entered from the opposite side of the stage and passed behind the screen, after which the state change occurred. In these experiments, for both state changes (collapsing and color change/sound, infants generalized their habituation to the contact event test trials, and recovered interest on the gap trials (Muentener & Carey,

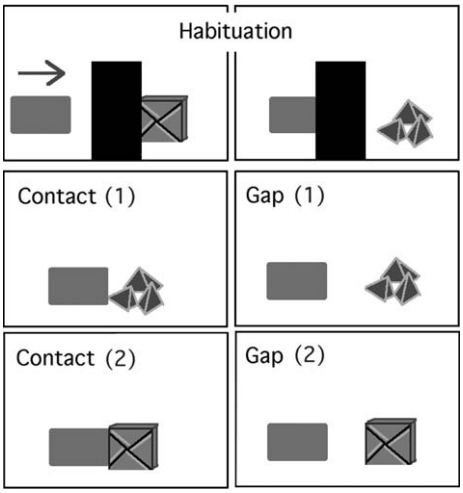

Fig. 6. Illustration of the paradigm used by Muentener and Carey (2006b), based on Ball (1973, see Fig. 1). In the habituation trials (top panels), Object A (a hand or a train, not shown) moved onto the stage and partly disappeared behind the central occluding screen. Immediately afterward, a block on the other side of the screen collapsed into size pyramidal pieces. For the test trials, the screen was removed. In the first experiment test trials (middle panels), infants saw Object A move in to the center of the stage, and then the block collapsed as in habituation. On alternating experiments, Object A either did make contact with the block just before it collapsed, or there was a spatial gap. Infants looked longer at the Gap test trials. In the second experiment test trials (bottom panels), infants saw the same sequence of events, except that the block never collapsed. These infants looked longer at the contact test trials.

2006a). Apparently, they can represent these state changes causally, but these ambiguous events require that the candidate situational agent (A) be a dispositional agent (human hand).

This experiment provides the same kind of evidence that children are representing causality as those cited above. Infants are shown several cases in which a two events co-occur (motion of A towards B is followed by a change in B). They are not provided any information about the actual interaction between A and B, for it is hidden by a screen. Nonetheless, they infer contact, a causally relevant feature of the interaction. In addition, their reasoning integrates other causally relevant information—whether A is a canonical dispositional agent. For these reasons, we conclude that infants are indeed representing the relation between the motion of A and the state change of B as causal. If this conclusion is warranted, one further prediction follows. Suppose infants are habituated to the collapsing box events as before. Suppose also that on test trials the screens are removed and infants are allowed to see the whole event, only now when the hand enters and either contacts the box or stops short, the state change does *not* occur. Now the relative looking time to the gap test events and the contact test events should reverse. It should be surprising if contact between the hand and the box does not result in a collapse, and it should not be surprising at all when the hand does not make contact with the box and no state change occurs. The looking time pattern reversed—infants looked reliably longer at the contact event than the gap event (Muentener & Carey, 2006a).

Besides providing further evidence that the infants interpreted these state changes causally, this last condition also ruled out an alternative interpretation of Muentener's original

result. Infants interpret hands reaching deliberately towards objects as intentional and goal directed (Woodward, 1998). The infants could conceivably have been representing the hand events merely as a goal-directed intentional act (the hand/person is reaching for the box), and predicted that goal-directed reaching typically ends with the hand in contact with the goal. Surely, contact is relevant to many relations among objects, not only causal ones. But, of course, if this were the right interpretation, the same pattern of looking should have obtained in the final study—the child should have expected the hand to reach the box whether or not the box collapsed.

Again, infants' representations of stable dispositional agency condition their interpretation of an ambiguous event as causal or not. More importantly, almost as young as they represent launching and entraining causally, infants reason about state changes (both a color/sound change and a mechanical collapse) causally. Young infants' causal representations transcend Michottean schema in two ways, both in their input (going beyond narrow spatio-temporal parameters) and in their output (going beyond launching, entraining and expulsion).

6. What's with hands?

Clearly, the studies reviewed above leave many important open questions. For example, it is important to know what properties of entities allow infants to identify them as dispositional agents or as inert objects. In all of the experiments sketched above testing infants' expectations about the entity in the agentive role of an interaction, the agent that infants accepted was a human hand. This was also the case in Leslie's study of dispositional agency. What is it about hands that make them good candidates to be the source of an inert object's motion, in contradistinction to a block (Leslie, 1984a; Saxe et al., in press), or a toy train (Muentener & Carey, 2006a, Saxe et al., 2005)? Have children merely learned that hands are typical pushers in launching events, throwers in expulsion events, smashers in distruction events, and entrainers in carrying events? Are they analyzing the mechanical affordances of hands vs. blocks, trains and sticks? Or, are they categorizing hands as self-moving agents with an internal source of causal power, reasoning that entities capable of self generated motion can also cause the motion of other entities?

In our lab, we have only one preliminary experiment addressing this question (Saxe et al., in press), and this is with slightly older infants (9.5 month olds). The paradigm is slightly different version of the 2-box paradigm described above. In this version children need not infer the existence of a previously unseen causal agent; rather, they must infer only an unobserved causal interaction. On each habituation trial, infants see one of two beanbags (a red one or a yellow one) emerge in flight from behind a screen (on the right side or the left side) and land in the middle of the stage in a pseudo-random order. Thus, while one beanbag emerges on every trial, the infants cannot predict which side the beanbag will come from on any particular trial. After habituation, the screens are lowered, revealing a hand behind one and a toy train behind the other. The screens are replaced and a beanbag immediately flies out from behind one of the screens. Infants generalize habituation to events in which the beanbag emerges from behind the screen where a hand is hidden, but they regain interest if it emerges from the screen where the train is hidden (Saxe et al., in press). This study provides convergent evidence to those described above that young infants represent stable causal dispositions and expect hands to be likely throwers in expulsion events, even if they do not see the actual causal interaction.

In an initial study that explores what it is about hands that make them good candidates to play the agentive role in these expulsion events, we replaced the hand in this paradigm with a small, furry, puppet with large eyes and spindly short legs. Prior to the study, infants were familiarized with the puppet, moving by itself on the stage. The experiment unfolded as described above, except on the test trials the screens were lowered revealing the puppet behind one and the train behind the other. 9.5-month-old infants accepted the puppet as a potential agent of the beanbag's motion; they regain interest only when the bean-bag emerged from the train-side (Saxe et al., in press). This result rules out the possibility that hands alone are represented as good throwers, or that infants are merely representing the mechanical affordances, or familiar actions, of potential agents (the puppet has no hands and no appendages that could throw, and the infant has never seen the puppet cause the motion of anything but itself). Left open is whether the important cues to dispositional agency are observed self-generated motion or the morphological features of people/animals (eyes, fur, legs). Future experiments will bring this paradigm down to 6- or 7-month-old infants, and will systematically explore the cues to dispositional agency that lead infants to accept an entity as a situational agent of the motion of an inert object in launching, entraining and expulsion events.

7. Conclusion: The origin of the capacity for causal representation

As Michotte would have predicted, the studies reviewed above suggest that young infants (by 6–7 months of age) perceive and interpret launching events, entraining events and expulsion events causally. The evidence is strongest for launching: infants are sensitive to the spatio-temporal features of the interaction between events that specify launching, treating events that satisfy them as categorically different from those that don't, while not distinguishing among the latter. Also, they assign different roles to the entities in a launching event, but not in events where the motion of one event merely follows another. In entraining events, as well, infants are sensitive to at least one causally relevant feature of the interaction—spatial contact. Further evidence that infants represent these events causally is their systematic and pervasive sensitivity to the dispositional causal status of the entities involved in the interactions. Their representation of dispositional agency affects their interpretation of entraining events, launching events, and expulsion events. This bolsters our interpretation that infants are reasoning causally—they are reasoning about the causes of motion of entities, and consider that the motion of dispositionally inert objects must be caused by contact with a moving entity, and that dispositional agents are better candidate causes of motion than are dispositionally inert entities.

The fact that infants' expectations about physical causal interactions are influenced so pervasively by the remembered dispositional agency of the inter-actants provides quite strong evidence against Michotte's hypothesis that perceptual causality is *the* source of causal representations. If the Michottean hypothesis was right, there should be a point in development at which we could find evidence for causal perception in fully visible launching or entraining events (as in the Leslie and Keeble studies or the Oakes and Cohen studies), and no evidence for causal inference, especially inferences integrating mechanical causality with other types of causal representations. No such point in development has been discovered yet; rather just the opposite is true. As soon as there is any evidence for causal representations, infants integrate their representations of the spatio-temporal parameters of events with information about the ontological status and stable

causal dispositions of the interacting entities. Similarly, if the Michottean hypothesis was right, there should be a point in development in which launching and entraining are represented causally, but causal interactions that he considered to be bootstrapped from the core causal sense (e.g., state changes) are not. Again, no such point in development has been discovered yet, and Muentener's data suggests that just the opposite is true.

The existing literature also does not provide any evidence for Michotte's claim that the perceptual input analyzer is innate, though there is no direct evidence against this claim yet, either. By the time experimentalists can find robust evidence of causal perception, infants have already had 6 months of experience observing causal interactions, presumably including launching, entraining and expulsion. More importantly, we have shown that other causal information (about the phenomenal and ontological aspects of objects) is integrated with representations of mechanical causality as young as we can find evidence that mechanical causality is itself represented. It is therefore possible that infants learn to recognise launching, entraining and expulsion as causal, by generalising from the sources of this "other" causal information—e.g., from the infants' own experience of effort, and/or from the analysis of conditional probabilities.

Of course, several possibilities concerning the origin of human causal representations remain open. It is possible that younger children would provide the requisite pattern of evidence—either for Michotte's candidate for the sole source of causal representations or for one of the others. It is also possible that all three mechanisms for identifying causal interactions in the world exist, are initially independent of each other, but have begun to be integrated already by 6 or 7 months of age. However, there is another possibility not anticipated in Michotte's debates with Main de Biran over the ultimate source of human causal representations. As the rationalists insisted, representations with the content *cause* may be innate, but they may be part of a central conceptual system that integrates information from all three sources of evidence (contingency, direct perception of mechanical causality, sense of one's own causal effort and efficacy in the world) from the outset. Given the rich interconnections between infants' representations of the sources of motion of inert objects and their representations of dispositional causal agents documented in the present studies, this alternative picture is very much alive.

References

Ball, W. A. (1973). The perception if causality in the infant. In: *Paper presented at the meeting at the society for research in child development*.

Berthenthal, B. I. (1993). Perception of biomechanical motions by infants: intrinsic image and knowledge-based constraints. In C. Granrud (Ed.), *Carnegie symposium on cognition: visual perception and cognition in infancy* (pp. 175–214). Hillsdale, NJ: Erlbaum.

Bertamini, M., & Hulleman, J. (2006). Amodal completion and visual holes (static and moving). *Acta Psychologica, 123*, 55–72.

Bhojani, K. (2006). *Hands as causal agents: seven-month-olds and the development of causal perceptions*. Harvard University, Undergraduate thesis.

Cheng, P. W., & Novick, L. R. (1990). A probabilistic contrast model of causal induction. *Journal of Personality and Social Psychology, 58*, 545–567.

Choi, H., & Scholl, B. J. (2004). Effects of grouping and attention on the perception of causality. *Perception and Psychophysics, 66*(6), 926–942.

Choi, H., & Scholl, B. J. (2006). Measuring causal perception: Connections to representational momentum? *Acta Psychologica, 123*, 91–111.

Cohen, L. B., Amsel, G., Redford, M. A., & Casasola, M. (1998). The development of infant causal perception. In A. Slater (Ed.), *Perceptual development: visual, auditory, and speech perception in infancy* (pp. 167–209). East Sussex, UK: Psychology Press Ltd.

Cohen, L. B., & Chaput, H. H. (2002). Connectionist models of infant perceptual and cognitive development. *Developmental Science, 5*, 173–175.

Dickinson, A., & Shanks, D. (1995). Instrumental action and causal representation. In D. Sperber, D. Premack, & A. Premack (Eds.), *Causal cognition: a multidisciplinary debate* (pp. 5–25). Oxford: Clarendon Press.

Fodor, J. A. (1983). *The modularity of mind*. Cambridge, MA: MIT Press.

Fulvio, J. M., & Singh, M. (2006). Surface geometry influences the shape of illusory contours. *Acta Psychologica, 123*, 20–40.

Garrett, D. (2006). Hume's theory of causation: inference, judgment and the causal sense. *Paper presented to the NNU philosophy conference at La Pietra*. Florence, Italy, June 6–8.

Gergely, G., Nadasdy, Z., Csibra, G., & Biro, S. (1995). Taking the intentional stance at 12 months of age. *Cognition, 56*, 165–193.

Gopnik, A., Glymour, C., Sobel, D. M., Schulz, L. E., Kushnir, T., & Danks, D. (2004). A theory of causal learning in children: causal maps and Bayes nets. *Psychological Review, 111*(1), 3–32.

Johnson, S., Slaughter, V., & Carey, S. (1998). Whose gaze would infants follow? The elicitation of gaze following in 12-month-olds. *Developmental Science, 1*, 233–238.

Kawachi, Y., & Gyoba, J. (2006). A new response-time measure of object persistence in the tunnel effect. *Acta Psychologica, 123*, 73–90.

Kosugi, D., & Fujita, K. (2002). How do 8-month-old infants recognize causality in object motion and that in human action? *Japanese Psychological Research, 44*(2), 66–78.

Kosugi, D., Ishida, H., & Fujita, K. (2003). 10-month-old infants' inference of invisible agent: distinction in causality between object motion and human action. *Japanese Psychological Research, 45*(1), 15–24.

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*(3), 344–359.

Leslie, A. M. (1982). The perception of causality in infants. *Perception, 11*, 173–186.

Leslie, A. M. (1984a). Infant perception of a manual pick-up event. *British Journal of Developmental Psychology, 2*, 19–32.

Leslie, A. M. (1984b). Spatiotemporal continuity and the perception of causality in infants. *Perception, 13*, 287–305.

Leslie, A. M., & Keeble, S. (1987). Do six-month old infants perceive causality? *Cognition, 25*, 265–288.

Muentener, P., & Carey, S. (2006a). Representations of agents affect infants' causal attributions. In: *Poster presented at the biennial meeting of the international society on infant studies*, Kyoto, Japan.

Muentener, P., & Carey, S. (2006b). What is the domain of causal reasoning? Investigating causal perception of motion and non-motion state change events in infancy. In: *Poster presented at the annual meeting of the vision sciences society*, Sarasota, Florida.

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

Oakes, L. (1994). Development of infants' use of continuity cues in the their perception of causality. *Developmental Psychology, 30*, 869–879.

Oakes, L., & Cohen, L. (1990). Infant perception of a causal event. *Cognitive Development, 5*, 193–207.

Pauen, S., & Trauble, B. (submitted for publication). Knowledge-based reasoning about the animate–inanimate distinction at 7 months of age: what makes the ball go round?

Pearl, J. (2000). *Causality, models, reasoning, and inference*. Cambridge, UK: Cambridge University Press.

Runeson, S., Juslin, P., & Olsson, H. (2000). Visual perception of dynamic properties: cue heuristics versus direct-perceptual competence. *Psychological Review, 107*(3), 525–555.

Saxe, R., Tenenbaum, J., & Carey, S. (2005). Secret agents: 10- and 12-month infants' inferences about hidden causes. *Psychological Science* (1001)*, 16*, 995.

Saxe, R., Tzelnic, T., & Carey, S. (in press). Knowing-who-dunnit: infants identify the causal agent in an unseen causal interaction. *Developmental Psychology*.

Schlottmann, A. (2000). Is perception of causality modular? *Trends in Cognitive Science, 4*, 441–442.

Schlottmann, A., Allen, D., Linderoth, C., & Hesketh, S. (2002). Perceptual causality in children. *Child Development, 73*, 1656–1677.

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.

Schlottmann, A., Surian, L., & Ray, E. (submitted for publication). Eight- and 10-month-old infants perceive action and reaction.

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

Spelke, E. S. (1985). Preferential looking methods as tools for the study of cognition in infancy. In G. Gottlieb & N. Krasnegor (Eds.), *Measurement of audition and vision in the first year of postnatal life* (pp. 323–363). Norwood, NJ: Ablex.

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.

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

White, P. A., & Milne, A. (1997). Phenomenal causality: impressions of filling in the visual perception of objects in motion. *American Journal of Psychology, 110*, 573–602.

White, P. A., & Milne, A. (1999). Impressions of enforced disintegration and bursting in the visual perception of collision events. *Journal of Experimental Psychology: General, 128*, 499–516.

Woodward, A. L. (1998). Infants selectively encode the goal object of an actor's reach. *Cognition, 69*(1), 1–34.