



SHORT REPORT

Causal learning from probabilistic events in 24-month-olds: an action measure

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Abstract

How do young children learn about causal structure in an uncertain and variable world? We tested whether they can use observed probabilistic information to solve causal learning problems. In two experiments, 24-month-olds observed an adult produce a probabilistic pattern of causal evidence. The toddlers then were given an opportunity to design their own intervention. In Experiment 1, toddlers saw one object bring about an effect with a higher probability than a second object. In Experiment 2, the frequency of the effect was held constant, though its probability differed. After observing the probabilistic evidence, toddlers in both experiments chose to act on the object that was more likely to produce the effect. The results demonstrate that toddlers can learn about cause and effect without trial-and-error or linguistic instruction on the task, simply by observing the probabilistic patterns of evidence resulting from the imperfect actions of other social agents. Such observational causal learning from probabilistic displays supports human children's rapid cultural learning.

Research highlights

- We examined toddlers' causal learning from probabilistic events using a two-choice action measure.
- The methods isolate *observational causal learning* as the underlying mechanism and separate it from causal linguistic descriptions or spatial contact.
- Toddlers learn the causal structure of probabilistic events from observing other people's actions and use this to generate their own actions to bring about the same effect on the world.

Introduction

Children's understanding of cause and effect is of fundamental importance to theories of cognitive development. Three competing views of the development of causal learning in young children have been proposed. Piaget (1928) originally proposed that children first learn about causality through the effects of their own motor actions – trial-and-error learning. A second set of

approaches focuses on causal events that involve spatio-temporal and physical-mechanical relationships. Michotte and followers (Leslie & Keeble, 1987; Michotte, 1963) suggest that children register causal relations prior to action, based on specific perceptual cues such as collision and launching – perceptual causality detection. More broadly, even infants seem to respond to such 'folk physical' causal relations as contact, covering, and containment (Baillargeon, Stavans, Wu, Gertner, Setoh, Kittredge & Bernard, 2012). Third, it has been argued that adult descriptions of events using causal language play a crucial role in children's learning about cause and effect – linguistic bootstrapping (Bonawitz, Ferranti, Saxe, Gopnik, Meltzoff, Woodward & Schulz, 2010; Spelke, 2003).

However, many important kinds of causal learning do not fall into these categories. Often we learn about causal relations in the world that are not the result of our own actions, are not explicitly described linguistically, and do not involve clear folk-physical mechanisms. These cases range from learning to operate a TV remote, to learning that whipping makes egg-whites puff, to learning that

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turning a faucet makes water come out. Recent studies suggest that very young children can learn causal relations like this and that social learning mechanisms can contribute to children's causal learning in ways that have been underestimated. Three- and 4-year-olds can infer causal structure from patterns of covariation without spatial contact between causes and their effects and without adults providing causal linguistic descriptions of the events during the test (e.g. Bonawitz *et al.*, 2010; Gopnik, Glymour, Sobel, Schulz, Kushnir & Danks, 2004; Gopnik & Wellman, 2012).

In one recent study, even much younger children, 24-month-olds, inferred causal relations from the goal-directed acts of other people—*observational causal learning* (Meltzoff, Waismeyer & Gopnik, 2012). In this study, 24-month-olds saw someone act on an object and produce a distant effect. Toddlers could use this information intelligently to bring about the effect themselves, without using trial-and-error, and in the absence of spatial or physical cues and adult causal linguistic descriptions. The 24-month-olds watched an adult perform the same action on two different objects. Doing the action on object-1 led to the effect, and doing the same action on object-2 did not. Then the children were given a chance to produce the effect themselves. The toddlers intervened on the causal object and predictively looked toward the effect before it happened.

The causal relations in the Meltzoff *et al.* (2012) study were deterministic. One critical unanswered question is whether observational causal learning at this age can incorporate *probabilistic* information. Inferring causal structure from probabilistic patterns of contingency is a well-established ability in adults (e.g. Cheng, 1997; Shanks & Dickinson, 1987; Waldmann, Hagmayer & Blaisdell, 2006), and has been demonstrated in studies with older children, albeit with the help of causal linguistic descriptions (Kushnir & Gopnik, 2005, 2007). However, previous work has not tested whether toddlers can infer causality from probabilistic contingencies.

Toddlers often observe probabilistic events. For example, they may see that pressing buttons on the television remote control often but not always changes the channel, or that turning a doorknob and pushing will often but not always open the door. The current study investigates whether 24-month-olds can learn about causal relationships from observing such events, and then use this knowledge to design actions of their own that will bring about an effect.

We know that early in development, infants implicitly register patterns of probability in *non-causal* contexts. They recognize probabilistic patterns in strings of language sounds, tones, and visual images (e.g. Bulf,

Johnson & Valenza, 2011; Kuhl, 2004; Saffran, Aslin & Newport, 1996; Wu, Gopnik, Richardson & Kirkham, 2011). They also form visual expectations about the likelihood of sampling a specific set of objects from a larger group of objects (Denison & Xu, 2010; Gweon, Tenenbaum & Schulz, 2010; McCrink & Wynn, 2007; Téglás, Girotto, Gonzalez & Bonatti, 2007; Téglás, Vul, Girotto, Gonzalez, Tenenbaum & Bonatti, 2011; Xu & Garcia, 2008). Young children might use this sensitivity to probabilistic patterns not only to form expectations about auditory or visual patterns, but also to make inferences about causal relations. Importantly, however, there have been no tests of whether infants can infer causal relations from probabilistic displays and act on such inferences.

How can we tell whether learners have inferred a causal relationship between A and B rather than just detecting an association between them? One 'gold-standard' test that has been proposed in the philosophical (Woodward, 2003) and psychological (Gopnik & Schulz, 2007) literature is to assess whether a learner can use the information to design a new action on the world. For example, contrast the relationship between having yellow, nicotine-stained fingers and getting lung cancer, and between smoking and getting lung cancer. In both cases we may accurately predict one variable from the other. But we will only *act* on one variable to influence the other if we think the relation is causal. Yellow fingers may predict cancer, but we would not start a hand washing campaign to prevent cancer, while we would start an anti-smoking campaign.

The ability to learn causal relations from observing imperfect evidence would be a valuable social learning mechanism for toddlers. Just as young children learn about speech from listening to patterns of input and social interchanges (e.g. Kuhl, Tsao & Liu, 2003; Saffran *et al.*, 1996), it would be useful for them to learn about causal relations among objects by observing the actions of others. We tested whether 24-month-olds can make use of observational causal learning from probabilistic contingencies.

Experiment 1

We presented 24-month-olds with a probabilistic causal display. The procedure followed a carefully controlled experimental protocol: (a) no causal linguistic descriptions were used by the experimenter during the study, (b) there was a spatial gap between the cause and the effect to avoid Michottean launching cues, and there were no physical/mechanical cues about the causal relationship, and (c) participants were not allowed any prior

experience handling the objects to rule out trial-and-error learning.

Two objects served as potential causes of a desirable event. The desirable event was a marble dispensing from a machine located 30 cm away from the objects (Figure 1). After observing this display, participants were given a chance to design an intervention to obtain the marble based on what they had observed.

Method

Participants

The participants were 32 24-month-olds, all within ± 14 days of their birthday ($M = 24.10$ months, $SD = 6.0$ days). An equal number of males and females were tested. An additional four toddlers began testing but were excluded due to sound sensitivity (one), and unwillingness to participate (three). Participants were recruited by telephone from the university's computerized participant pool. Pre-established criteria for admission into the study were that the children be full-term, normal birth weight, and have no known developmental concerns. The sample was primarily middle- to upper-middle-class with 78% White, 6% Asian, 16% Other, and 9% of Hispanic ethnicity according to parental report.

Stimuli

Two sets of wooden objects were used which differed from each other in both shape and color. The set used during the familiarization phase consisted of a green egg (6 cm \times 4 cm) and a yellow square (7 cm \times 7 cm). The set used during the test trial consisted of a red cylinder (7.5 cm \times 3.25 cm) and a blue hemisphere (4.75 cm \times 9.75 cm). When placed on the table, the objects were arranged on a tray with a box in the middle and the two

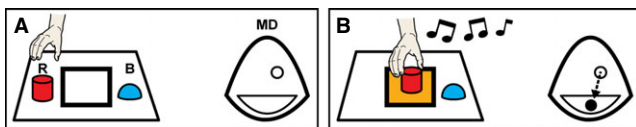


Figure 1 A schematic display showing the causal chain of events used in Experiments 1 and 2. (A) Two colored, wooden objects depicted by the red cylinder (R) and the blue hemisphere (B), serve as potential causes of a chain of events that leads to the activation of a marble dispenser (MD). (B) When placed on a box, the box illuminates (orange highlight) and emits a sound (musical notes). This event is immediately followed by the marble (black dot) dispensing from the marble dispenser. A 30-cm gap separated the box and the marble dispenser. (Figure is not drawn to scale, see text for measurements).

objects on either side (Figure 1A). The marble dispenser was situated to the toddler's right near the edge of the table. When either object was placed on the box, it always caused the box to illuminate and emit sound (Figure 1B). On 'effective' demonstrations only, a marble was immediately dispensed from the marble machine and placed on a marble run (the 'effect'), which was highly desirable for the children.

Procedure

Toddlers were tested in the laboratory while seated on their parent's lap at a black table (72 cm \times 120 cm). All responses were video-recorded. The objects were out of reach of the child, approximately 15 cm from the adult's side of the table. The experimental protocol consisted of a short familiarization phase and then the test trial. The test trial consisted of children observing probabilistic events (the 'stimulus-presentation period') followed by a 30-s period when the test objects were presented to the children to manipulate ('response period').

Throughout the experiment, the adult used everyday social-interactive cues such as infant-directed speech and mutual gaze with the child (Csibra & Gergely, 2011), but crucially, the experimenter did not provide any causal linguistic description of the events. For example, the adult said, 'Let's watch' but did not narrate the events using causal language such as 'I'm using the block to make it go' or 'I'm going to make this work.' This safeguard was followed because past work suggests that causal descriptions in particular can change children's performance on causal learning tasks (e.g. Bonawitz *et al.*, 2010). The experimental protocol thus incorporated attention-getting, pedagogical cues (Csibra & Gergely, 2011), see below for quantification, but excluded causal linguistic descriptions of the displays.

Familiarization phase. Because the procedure and apparatus were novel, toddlers were first familiarized to the general nature of the game. During familiarization, the warm-up objects (which were not the same ones used during the test trial) were deterministically effective in producing the effect: When the experimenter placed one object on the box, the desired effect always occurred (4 out of 4 times; 100% effective); when the experimenter placed the other object on the same box, the desired effect never occurred (0 out of 4 times; 0% effective). Following this, all toddlers were given a choice to place one of the two objects on the box and then presented with the second object to place on the box. All 32 participants did so, and thus all of them placed both objects on the box an equal number of times. This familiarization phase showed children that their own actions could result in distant outcomes and that

Table 1 Probabilistic activation patterns shown to 24-month-olds

| | Activation Pattern | Object 1 → | Object 2 → | Object 1 → | Object 2 → | Object 1 # effective actions | Object 2 # effective actions |
|--------------------------|--------------------|-------------|-------------|-------------|-------------|---------------------------------|---------------------------------|
| Experiment 1 Patterns | 1 | 1-1-0 | 1-0-0 | 1-1-0 | 1-0-0 | 4 of 6 | 2 of 6 |
| | 2 | 1-0-0 | 1-1-0 | 1-0-0 | 1-1-0 | 2 of 6 | 4 of 6 |
| | 3 | 0-1-1 | 0-0-1 | 0-1-1 | 0-0-1 | 4 of 6 | 2 of 6 |
| | 4 | 0-0-1 | 0-1-1 | 0-0-1 | 0-1-1 | 2 of 6 | 4 of 6 |
| Experiment 2 Patterns | 1 | 1-1-0 | 1-0-0-1-0-0 | 1-1-0 | 1-0-0-1-0-0 | 4 of 6 | 4 of 12 |
| | 2 | 1-0-0-1-0-0 | 1-1-0 | 1-0-0-1-0-0 | 1-1-0 | 4 of 12 | 4 of 6 |
| | 3 | 0-1-1 | 0-0-1-0-0-1 | 0-1-1 | 0-0-1-0-0-1 | 4 of 6 | 4 of 12 |
| | 4 | 0-0-1-0-0-1 | 0-1-1 | 0-0-1-0-0-1 | 0-1-1 | 4 of 12 | 4 of 6 |

Note '1' indicates an effective event; '0' indicates an ineffective event. The time course for each pattern proceeds as read from left to right, following the arrows. Each infant was randomly assigned to observe one pattern during the stimulus-presentation phase, with eight infants randomly assigned to each row.

there was a 'cost' to choosing an object – it may or may not be effective.

Probabilistic test trial. Toddlers were presented with the probabilistic test trial using a set of distinctive objects that differed visually from the familiarization objects in both shape and color.

Stimulus-presentation period: Toddlers observed as the experimenter placed one of the objects on the box three times in a row, followed by the experimenter placing the second object on the box three times in a row. After a pause of approximately 15 s, the experimenter repeated this sequence again (see Table 1).

During the stimulus-presentation period, the marble dispensation (the desired effect) occurred *probabilistically*. When the experimenter placed one object on the box, the marble dispensed four out of the six times she did so. This object was termed the 'high-probability cause' – the probability of it being effective was .67. When the experimenter placed the other object on the same box, the marble dispensed two out of six times. This was termed the 'low-probability cause' – the probability of it being effective was .33. This sequence of 12 events, six with each object, constituted the probabilistic activation pattern for that infant. There were four possible activation patterns in Experiment 1 (see Table 1).¹

As shown in Table 1, the probabilistic activation patterns were designed to control for low-order cues for choosing Object 1 versus Object 2. For half of the toddlers, the high-probability object was used first; for the other half the low-probability object was used first. Thus, choosing to intervene on the object the adult used

first would result in responding at chance levels (.50 correct). Moreover, for any single toddler (reading across a row in Table 1), the pattern for both objects began with the same type of event, either effective or ineffective at producing a marble, and both ended with the other type of event, either effective or ineffective. Thus, toddlers could not use either the 'first observed event' (primacy) or the 'last observed event' (recency) to determine which object to intervene on.

The experiment was also counterbalanced with respect to: the sex of the child, which object was the higher probability object, and the side on which the higher probability object was located. This counterbalancing, coupled with using novel objects in the test trial that had not been part of familiarization, was designed to prevent children from solving the problem based on a simple generalization from the familiarization phase – although toddlers in the familiarization may have learned that there was a 'cost' to not choosing correctly, this, in itself, would not give them information about *which* object to choose in the test trial.

Response period: Following the stimulus-presentation, toddlers were administered a response period during which the two potential causal objects were presented side by side, separated by a distance of 45 cm. If 24-month-olds are able to make inferences from the observation of probabilistic causal patterns, they should select the high-probability object and put it on the box (this is the correct 'intervention'). Perceiving a statistical pattern alone, without making the causal connection, is not sufficient to solve the task, because the test used an action measure requiring toddlers to choose between two objects and use the selected one in a particular way (place it on the box). Moreover, duplicating the experimenter's motor actions also would not solve the task, because the experimenter placed *each* object on the box an equal number of times.

¹ This sequence of events, although relatively short, allows observers enough information to make a reasonable judgment, or 'best bet' about which object is more likely to produce the desirable effect.

Dependent measures and scoring. The principal dependent measure used in the main analysis was the child's first response (picking up an object *and* placing it on the box). These responses, as well as the manipulation check of the experimental procedure (see below), were scored from the video records of the study in a random order by a coder who was blind to the test conditions. The coders viewed video segments of the response periods, which contained no clues about which object was the high- versus low-probability object – the segments were identical regardless of the stimulus-presentation. For the principal dependent measure, 25% of the videos were re-scored by a second coder, who was also kept blind, and there were no intra-coder disagreements, Cohen's kappa was 1.00.

Results and discussion

Manipulation check

The manipulation check confirmed that the experimental protocol was rigorously followed. Video review revealed that causal linguistic descriptions were never used. The experimenter's use of infant-directed speech, mutual gaze, and the child's name did not differ as a function of whether the experimenter was using the high- or low-probability object. Infant-directed speech was used on all events (regardless of whether the experimenter was using the high- or low-probability object). Children's names were used only three times across all children (one time for a high-probability object and two times for a low-probability object). Mutual gaze (the number of times the experimenter looked towards the child while the child was looking at her) did not significantly differ as a function of high- or low-probability object, $t(31) = 1.49$, $p = .15$.

Main analyses of causal learning

Twenty-four-month-olds systematically chose the correct intervention, placing the high-probability causal object on the box significantly more often than would have been expected by chance (23 of 32 participants, binomial test, $p = .02$, $g = .22$). Children seemed to pick up the high-probability object with the intent to bring about the effect: This can be quantified by reporting that mean latency to perform the target act was less than 2 s ($M = 1.83$ s, $SD = 0.89$ s) after first touching it. All toddlers were highly attentive during the stimulus-presentation phase. Toddlers' gaze was directed at the displays approximately 98% of the time ($M = 98.27\%$, $SD = 2.79\%$).

The results show that toddlers can perform causal interventions after observing probabilistic displays.

There are at least two ways toddlers might achieve this. One way would be to use the *likelihood* of the effect – using the relative probability of each object producing the effect (.67 vs. .33) or estimating the ratio of successes to failures for each object. Another way would be to use the *frequency* of successes, that is, the absolute number of times the effect occurred when each object was placed on the box. The high-probability object activated the marble dispenser four times, while the low-probability object activated it only twice. Perhaps when faced with a choice, toddlers plan their interventions based on the frequencies instead of using the evidence observed across the entire probabilistic display (i.e. relative probabilities or ratios). This was tested in Experiment 2.

Experiment 2

Method

Participants

Participants were 32 naïve 24-month-olds, ± 14 days of their birth date ($M = 24.2$ months, $SD = 6.6$ days). An equal number of males and females were tested. An additional 11 toddlers began testing but were excluded due to experimenter or equipment error (five), sound sensitivity (one), and unwillingness to participate (five). All participants were recruited as in Experiment 1. The sample was primarily middle- to upper-middle-class with 81% White, 3% Asian, 9% Other, and 6% of the sample was of Hispanic ethnicity.

Procedure

Toddlers participated in the same general procedure used in Experiment 1 with one key modification: The frequency of the effect was identical for both objects, although their probabilities varied. The high-probability object produced the effect four out of the six times it was placed on the box; the low-probability object produced the effect four out of 12 times.

The objects used for familiarization and the test trial were the same as in Experiment 1, and the order of presentation for the high- versus the low-probability object during the test was counterbalanced as in Experiment 1. The experimenter placed one of the objects on the box three times in a row (activating the effect twice, .67) and then placed the other object on the box six times in a row (activating the effect twice, .33). After a 15 s pause, the sequence was repeated. This sequence of 18 events constituted the probabilistic activation pattern for

a given child. There were four possible activation patterns in Experiment 2 (see Table 1), with eight participants randomly assigned to each. If 24-month-olds are limited to using frequency information about probabilistic displays, their performance should drop to chance. Participants were scored in the same manner as described in Experiment 1, except that two children did not have a video record of their behavior. Instead the main analyses for those two children were done based on a live scoring of their session. There were no coder disagreements, Cohen's kappa was 1.00.

Results and discussion

Manipulation check

As in Experiment 1, the experimental protocol was rigorously followed. Causal linguistic descriptions were never used. This study equated for the frequency of producing the effect, and thus there were necessarily more events with the low-probability object (see Table 1). However, each individual instance of using the low- or high-probability object was highly similar: Infant-directed speech always occurred, children's names were used two times across all children (both times for a low-probability object), and the occurrence of mutual gaze was no different as a function of whether the high- or low-probability object was used, $t(29) = 0.70$, $p = .49$.

Main analyses of causal learning

As in Experiment 1, all 24-month-olds were attentive: Toddlers' gaze was directed at the displays approximately 95% of the time ($M = 94.90\%$, $SD = 5.54\%$). Toddlers chose the correct intervention by placing the high-probability object on the box significantly more often than the low-probability object (22 of 32 participants, binomial test, $p = .05$, $g = .19$). Children's latency to perform the target act after first touch of the high-probability object was less than 2 s ($M = 1.86$ s, $SD = 0.71$ s).

Success on this task suggests that toddlers can use the likelihood of an effect rather than the frequency of the effect when planning their own interventions. Explanations based solely on low-order cues, such as first or last object used or other counterbalanced factors, are ruled out; but as in other studies examining infant learning from probabilistic displays, toddlers could have responded based on heuristics other than the low-order ones we controlled for (Denison & Xu, 2010; Saffran *et al.*, 1996). For example, the heuristic might be the number of times an object is ineffective or an avoidance of objects associated with more ineffective events. We

controlled for number of times an object was effective (both objects in Experiment 2 produced the effect four times), but not the number of times an object was ineffective.

However, it is worth noting that previous work using non-causal probabilistic displays reveals that younger infants can use relative proportions rather than heuristics such as avoidance of dis-preferred objects or frequency/quantity information. Denison and Xu (2014) reported that 10- to 12-month-old infants make predictions about the location of a desirable object based on proportions rather than avoidance of dis-preferred objects or choosing based on observed quantities. This is also compatible with previous work showing that 8-month-olds distinguish speech stimuli based on differences in probabilities rather than the frequency of co-occurrence of syllables (Aslin, Saffran & Newport, 1998). Future studies could continue to explore this using probabilistic causal displays such as those described here.

General discussion

The results of Experiments 1 and 2 show that 24-month-olds learn about cause and effect from observing the actions of social agents. They can do so even when those actions are not deterministic, when the cause and effect are spatially remote from one another with no clear physical mechanism connecting them, when causal linguistic descriptions of the events are not used in the experiment, and when the participants have not manipulated the objects prior to testing. Critically, the current work shows that toddlers can use this information to plan their *own causal actions*—they execute their own 'interventions' to bring about the same effect.

Toddlers succeeded without the support of causal descriptions or spatial contact between the cause and the effect, but it remains to be seen what other features are necessary for toddlers to succeed. They may be particularly motivated to act on causal evidence that has social origins. Previous studies suggest the idea that infants and toddlers have difficulty learning from the observation of deterministic causal events that are not the result of human actions (e.g. Bonawitz *et al.*, 2010; Futo, Téglás, Csibra & Gergely, 2010; Meltzoff, 2007; Meltzoff *et al.*, 2012). It therefore seems unlikely that toddlers would be equally competent on the current probabilistic task if it did not involve actions produced by a social agent, but this remains to be tested.

Similarly, the adult used everyday interactive cues such as eye contact and infant-directed speech, and these cues (Gergely & Csibra, 2013) as well as the agent herself may support children making these causal inductions, but

again this awaits further testing. Also of interest is the durability and generalizability of the causal learning—in the current study, the memory demands were minimal and the test occurred in the same context as the learning.

Our findings support the inference that 24-month-olds use their sensitivity to statistical patterns to learn the causal structure of the physical world at remarkable speed, despite the uncertain evidence they receive. Toddlers' ability to *act* on the physical world—to design and conduct their own interventions based on observed probabilistic evidence—provides them with a robust mechanism for learning many different types of causal relations, including culturally specific ones. Watching the outcomes of others' actions can indicate which causal relationships are most important to master in a particular culture (Gopnik, 2012; Meltzoff, Kuhl, Movellan & Sejnowski, 2009). Toddlers observe that an adult pushing buttons or twisting a doorknob does not always achieve the desired effect. Nevertheless, they can use that information to design their own interventions and bring about desired effects in the world.

Acknowledgements

This research was supported by grants from the James S. McDonnell Foundation and NSF (SMA-0835854, BCS-1023875, and DRL-1251702).

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Received: 22 July 2013

Accepted: 1 May 2014