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One-year-old infants use teleological representations of actions productively

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Abstract

Two experiments investigated whether infants represent goal-directed actions of others in a way that allows them to draw inferences to unobserved states of affairs (such as unseen goal states or occluded obstacles). We measured looking times to assess violation of infants' expectations upon perceiving either a change in the actions of computer-animated figures or in the context of such actions. The first experiment tested whether infants would attribute a goal to an action that they had not seen completed. The second experiment tested whether infants would infer from an observed action the presence of an occluded object that functions as an obstacle. The looking time patterns of 12-month-olds indicated that they were able to make both types of inferences, while 9-month-olds failed in both tasks. These results demonstrate that, by the end of the first year of life, infants use the principle of rational action not only for the interpretation and prediction of goal-directed actions, but also for making productive inferences about unseen aspects of their context. We discuss the underlying mechanisms that may be involved in the developmental change from 9 to 12 months of age in the ability to infer hypothetical (unseen) states of affairs in teleological action representations.

Keywords: Infancy; Theory of mind; Teleological reasoning

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1. Introduction

People as well as children tend to interpret other people's behavior as goal-directed actions (Bekkering, Wohlschlager, & Gattis, 2000; Zacks, Tversky, & Iyer, 2001) and they extend these interpretations to the behavior of other animals and even to inanimate moving objects (Heider & Simmel, 1944). These goal-attributions are usually, but not necessarily, accompanied by mental state attributions as well (Abell, Happé, & Frith, 2000; Gergely, 2002). Recently more and more evidence suggests that, by the end of the first year of life, infants begin to interpret observed actions in terms of goals (Csibra, Gergely, Bíró, Koós, & Brockbank, 1999; Gergely, Nádasdy, Csibra, & Bíró, 1995; Meltzoff, 1995; Woodward, 1999; Woodward & Sommerville, 2000). In fact, several theorists proposed various versions of the idea that this precocious ability reflects the first step towards the development of a fully-fledged "theory of mind" (attention-goal psychology: Baron-Cohen, 1993; teleological stance: Csibra & Gergely, 1998a; ToMM system 1: Leslie, 1994).

We consider an action goal-directed if it is performed in order to bring about a change of state in the world, i.e., if it is a means to an end. We can intuitively test whether an action is a means to a goal or not by considering whether one would expect to see it performed even if it was no longer needed to achieve the goal. Assume, for example, that we see Tim in his office speaking on the phone to talk to his wife at home. That Tim's action is a means to a goal is indicated by the fact that we would be quite surprised to see him perform the same action if his wife was standing next to him in his office.

We can illustrate this point by a recent study that demonstrated that 1-year-olds can tell means and ends apart. Woodward and Sommerville (2000) presented infants with two transparent boxes that contained two different toys. They habituated the infants to an action (Experiment 1, embedded-action condition) in which a hand first touched one of the boxes, then opened it and grasped the toy inside. After habituation the toys were swapped between the boxes. During the test event the hand either touched the same box as before (which, however, now contained the other toy) or it touched the other box (which contained the same toy that had been previously grasped). Infants looked longer at the former action, indicating that they did not expect the hand to perform the familiar action seen before, as that was no longer necessary to obtain the goal object (i.e., the toy that had been grasped during habituation). In a control study (Experiment 2) Woodward and Sommerville habituated the infants to the same hand actions (first touching the box, then grasping the toy) with the exception that the toys were not inside but in front of the boxes, hence opening the box could not have been considered as a means to grasp the toy. In this condition, the infants did not develop any specific expectation about which box the hand should touch when the toys were swapped and, in fact, they even looked slightly longer when the hand touched the other box.

This study is a clear demonstration that 12-month-olds interpret an action in terms of means and ends, i.e., as a goal-directed action. Woodward and Sommerville argued that the understanding that the hand's touching the box in the experimental condition is a means to a goal is made possible by the infants' comprehension of the "causal constraints" that link the action to the goal in the given situation. While the authors are probably right in claiming that understanding the causal constraints in question are necessary for interpreting the action as goal-directed, we believe that there is an important further factor that needs to be taken into account and that is missing from Woodward and Sommerville's explanatory account. Undoubtedly, the infants had to comprehend the causal constraints that an object can only be retrieved from a closed box after it has been opened and that the hand's touching the box is causally relevant to opening it. However, physical knowledge of this kind provides only a *negative* constraint; it tells us only what one can or cannot do, but does not tell us what one should or should not do to achieve the goal. In other words, it does not explain why, in the control study, touching the box is *not* interpreted as a part of the goal-directed action; after all, it did not prevent the hand from obtaining the toy eventually. In fact, the results indicate that infants expected the hand *not* to perform unnecessary, unjustified actions, and when it did perform such an action, as in the control condition where the toys were outside the boxes, it was not considered as a means to the goal. This expectation is indeed very much in line with what we, adults, do in similar situations. As philosophers like Fodor (1987) and Dennett (1987) have emphasized, applying a theory of mind entails the assumption that agents behave in a *rational* manner—otherwise we would not be able to predict from their beliefs and desires what particular action they can be expected to perform. Briefly, the rationality assumption predicts that an agent will carry out the most effective or rational action available, under her specific criteria, that would achieve the state represented by her desires in the world represented by her beliefs. Demonstrating that infants also apply the rationality principle[1] in the interpretation of simple actions, in fact, proves that they do not simply rely on their understanding of the physical causal constraints that apply in a situation, but that they also make use of a central inferential component of the adult's theory of mind (that acts as a well-formedness criterion on teleological action representations, see below).

In fact, in our earlier studies, we have provided evidence that infants' can rely on the rationality principle to make sense of goal-directed actions even earlier (already by 9 months of age) than Woodward and Sommerville study would suggest and that this ability is not restricted to the interpretation of actions performed by humans (Csibra et al., 1999; Gergely et al., 1995). In these studies a computer-animated geometric figure performed a means (jumping over an obstacle) to achieve a goal state (a spatial position next to another figure). After habituation, the situation was changed in a way that the jumping action was no longer required to achieve the goal state: the obstacle was removed. The infants were then confronted with either the same jumping action as before or a novel straight approach that was, however, more appropriate (efficient) to achieve the same goal in the new situation. Just like in the Woodward and Sommerville study, infants looked longer at the event consisting of the familiar action that was no longer a rational means to the goal, indicating that they expected the action to change in the new situation. Note that our events did not involve any human action, and our subjects succeeded on our test already at 9 months of age.

We proposed (Gergely & Csibra, 1997) that the interpretation underlying infants' performance (as well as the corresponding adult intuition) in these tasks can be formalized in the following way (Fig. 1). A goal-directed action is represented in terms of a teleological interpretational schema containing three elements: the observed behavior, a possible future state (future in relation to the behavior), and the relevant aspects of physical reality that constrain possible actions. This schema provides a *well-formed* teleological representation only when the observed behavior can be considered as an effective (rational) way to bring about the future state given the physical constraints of the particular situation. If this well-formedness condition

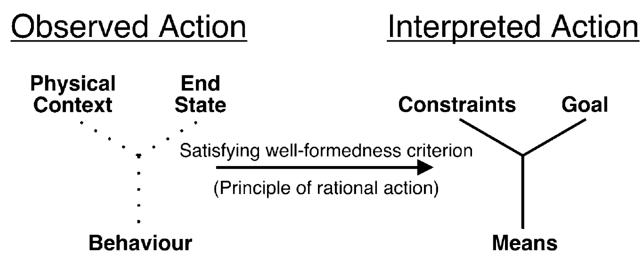

Fig. 1. Teleological representation of goal-directed action.

(articulated by the rationality principle) is satisfied by the representation in question, the future state will become encoded as the goal, the behavior as a means to the goal, and the relevant aspects of physical reality as action constraints (Fig. 1). Therefore, it is the principle of rationality that specifies the well-formedness conditions which, when satisfied, relates together the three elements of the representation of the teleological schema, creating the interpretation of the observed behavior as a goal-directed action.

Note, however, that the rationality principle not only functions as a criterion of well-formedness; it can also act as an active inferential principle: from knowledge of the contents of any two elements of a teleological representation, it makes it possible to infer (predict) the likely content of the third element, when that is not directly known. The studies discussed above (Csibra et al., 1999; Gergely et al., 1995; Woodward & Sommerville, 2000) demonstrated one type of such inference: namely, predicting the new means as a function of the known goal and the changed physical constraints on action. During habituation, the infants in these studies could set-up a well-formed teleological representation of the goal-directed action, because the observed behavior could be interpreted as an effective means to bring about the goal state within the constraints of the given situation. During the test phase, the infants were confronted with a modified situation in which some relevant constraining aspects of physical reality had been changed (removal of the obstacle; swapping the toys). On the assumption that the goal state did not change, they could now use the rationality principle to infer a new behavior that would effectively lead to the same goal within the new constraints, i.e., they could predict a new means to the same goal (straight-line approach; touching the other box). Note that the control conditions did not enable such predictions, because in the habituation events the observed behavior could not be represented in a well-formed teleological representation as an effective means to the goal in the first place.

The above studies demonstrated only the above type of inference: predicting new means from known goals and reality constraints. In principle, however, there are two other types of inference that can be generated from incomplete teleological representations using the rationality principle: inferring (unseen) goals from observed actions and reality constraints, and inferring (unseen) reality constraints from observed actions and goal states. Thus, the formal description and well-formedness conditions of the teleological representational schema that is needed to interpret goal-directed actions has led us to the predictions that, if infants can set-up well-formed teleological representations for goal-directed actions, then they should be able to perform these new types of inferences as well. Experiments 1 and 2 were designed to test these predictions.

2. Experiment 1

People do not have to observe a complete action to attribute a goal to it. While observing the end state of an action is sometimes the best evidence about what the action has been directed at, it is neither necessary for goal-attribution, nor does it indicate unambiguously what the goal is. Baldwin and Baird (2001) demonstrated that both adults and infants find it odd if an ordinary action is interrupted before its normal end point, probably because they guess and anticipate the end state of the action and detect the mismatch between the anticipated and the observed end state. In certain circumstances, we even attribute counterfactual goals to actions, i.e., goal states that do not correspond to the observed end state. These are the situations when an action is interpreted as failing to achieve its intended end state: when its observed outcome differs from its intended goal. Meltzoff (1995) demonstrated that 18-month-old babies could infer from apparently failed attempts the intended goal of the action that they have not actually seen realized. When his subjects had a chance to imitate a model's failed actions performed on novel objects, they did not copy the failure, but performed the complete intended action that led to the goal state that they had inferred from the model's behavior. Similarly, Carpenter, Akhtar, and Tomasello (1998); see also Woodward (1999) demonstrated that 14- to 18-month-olds can recognize whether an action is intentional (hence goal-directed) or accidental and tend to imitate the intentional action only. Importantly, in making this distinction the infants relied on behavioral cues (such as accompanying vocalizations like "Oops!" or "There!"), rather than on the end state of the action.

Further evidence for goal-attribution without direct observation of the outcome comes from animation studies. On the basis of its motion pattern, people quickly identify a "wolf" among a "flock of sheep" as it consistently approaches a "target," while the sheep move about randomly (Dittrich & Lea, 1994). The results of Rochat, Morgan, and Carpenter (1997) suggests that young infants are also sensitive to the relational motion cues that may be relevant to goal-attribution. Even 3-month-olds could discriminate between displays showing two figures moving either independently or chasing each other. Although this result provides no direct evidence for goal-attribution, it nevertheless indicates that infants are sensitive to the inter-relatedness of movement patterns that can be essential in evaluating goal-approach.

These bits of evidence suggest that both adults and infants can attribute goals to actions that they have not seen completed. What is the basis for such goal-attributions? In accord with some philosophers (e.g., Dennett, 1987), we hypothesize that people rely on the rationality assumption when trying to find a suitable goal for an incomplete action. Unlike in action *prediction*, where the rationality principle is used to infer what the appropriate means to an end would be in a given situation, attributing a goal to an incomplete action involves action *explanations*, where the rationality principle works "backwards": it helps to identify an end state that would justify the behavior as being a rational goal-directed action. We have shown that 9- and 12-month-old infants can use the rationality principle to predict the goal-directed actions of computer-animated figures (Csibra et al., 1999; Gergely et al., 1995). The present experiment addressed whether they could also apply the same principle in an explanatory situation, i.e., to infer the end state of an action that is not visible to them.

In this experiment we applied the same logic as in our earlier studies. Infants were repeatedly presented with an animated event involving two objects, which adults would readily interpret as a chasing event. However, the objects left the computer screen before the "chaser" could have caught up with the "chasee" and so the goal of catching the chasee had never been actually observed: it had to be inferred. After habituation, the physical environment within which the chasing event took place was modified in a way that would have required an adjustment of the chaser's action for it to be justified as rational, assuming that it continued to pursue the same goal as before. If infants rely on the assumed rationality of the action when attributing a goal to it, they should predict the appropriate behavioral adjustment of the chaser's action in the new situation. However, they should not predict a change of action in the new circumstances if, as in our control condition, the action observed in the habituation phase could not have been interpreted as a well-formed rational action towards an invisible goal state in the first place.

2.1. Method

2.1.1. Participants

Fifty-six 12-month-old (24 males and 32 females, mean age = 369.2 days, *SD* = 8.0 days, range 351–381 days) and 28 9-month-old (13 males and 15 females, mean age = 273.5 days, *SD* = 9.1 days, range 255–291 days) infants participated in the study. An additional 13 12-month-old and 1 9-month-old infants were also tested but were excluded from the data analysis because of fussiness or short looking times (see Section 2.1.4) during the test trials (five 12-month-old and four 9-month-old babies). Half of the 12-month-olds (28 infants) were assigned to the experimental group; the other half formed the control group. The 9-month-olds participated only in the experimental condition. All the infants were healthy, full-term infants living in the Greater London area recruited through advertisements.

2.1.2. Apparatus

The infants sat in their parent's lap in a darkened experimental room looking at an 18 cm × 24 cm monitor placed at eye level from a distance of 1.2–1.4 m. A video camera focusing on the baby's face was mounted above the monitor peeping through the opening of a black curtain, which allowed the experimenter to monitor the infant's eye fixations.

2.1.3. Stimuli

The habituation and test stimuli were computer-animated events involving two characters: a yellow circle ("chasee") and a red circle ("chaser"). The only difference between the events for the experimental and control group was the size of the chaser: its diameter was 1.3 cm in the experimental condition and 0.3 cm in the control condition. The diameter of the chasee was 0.5 cm. There were also two aligned horizontal black bars on the screen with a width of 0.8 cm and a length of either 2.8 cm (habituation event) or 1.3 cm (test events). There was a gap between the two bars that was 0.7 cm wide in the habituation event and 3.7 cm wide in the test events. The characters and bars appeared on a green background.

Each event started with the two bars appearing in the upper left quadrant and the chaser in the lower right corner of the screen (see Fig. 2). After 540 ms, the chasee appeared at the bottom left corner, started to move along a straight path passing through the middle of the gap between the two bars at a 4 cm/s constant speed, and eventually leaving the screen at the top edge of the screen. As soon as the chasee entered, the chaser started to follow it in a heat-seeking fashion,

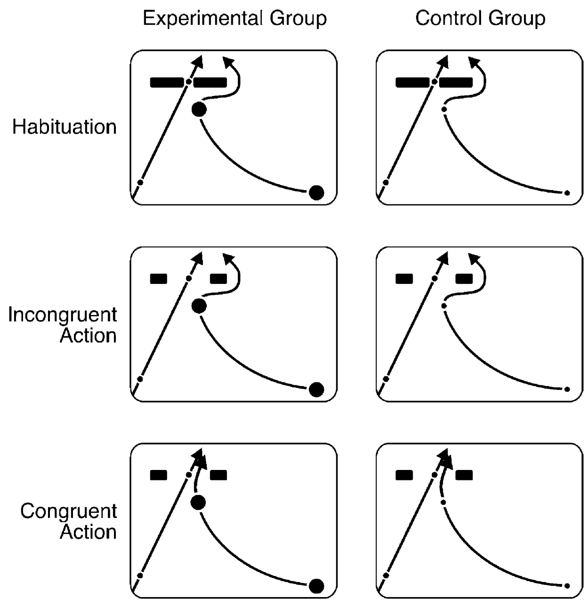

Fig. 2. Schematic representation of the animations used in Experiment 1.

i.e., its direction of motion was pointed towards the chasee. Its speed was also constant at 5.2 cm/s. During the habituation event, the gap between the bars was narrow (0.7 cm). When the chasee passed through the gap, the chaser changed its path, making a detour around the bar on the right side, and then left the screen in the direction where the chasee had disappeared. Note that, had it been a real object, the chaser could not have been able pass through the narrow gap in the experimental condition (big chaser), while it could have done so in the control condition (small chaser). During the test events the gap between the bars was widened (3.7 cm). The chaser behaved exactly the same way in the Incongruent Action test event as in the habituation event, i.e., it made a detour around the bars instead of passing through between them. In the Congruent Action test event, however, it did not perform a detour, but continued to follow the chasee through the gap, continuously reducing the distance between them.

The chaser left the screen 5.6 s after it started to move. The event ended 540 ms later when the two bars disappeared, leaving a blank screen. The event was repeated again following a 1 s pause.

2.1.4. Procedure

At the beginning of each trial, the experimenter drew the infant's attention to the display by presenting colored flashes on the monitor. When the baby looked at the screen, the experimenter pressed a key that started the presentation of the stimulus event, which was then repeated continuously until the infant looked away for more that 2 s. When the infant looked away, the experimenter released the key on the keyboard, and if she did not press it again within 2 s indicating that the infant looked back again, the computer program stopped the stimulus display and registered the looking time for the trial. When the infant looked at the screen again, the next trial was started. A trial had to last at least 2 s to be treated as valid, i.e., if the infant looked at the event for less than 2 s, the trial was ignored. The computer program calculated the average fixation time for the first three habituation trials and compared this value on-line with the running average of the last three fixation times. We used a habituation criterion that required that the average fixation time for the last three trials be less than half of the average looking times for the first three habituation trials. Thus, the minimal number of habituation trials was 6.

After the habituation criterion was reached, a 30-s long break was introduced during which the mother, who was sitting on a swivel chair, was asked to turn with her baby away from the monitor. When they turned back and the test trials started, we instructed the mothers to close their eyes so that they could not inadvertently bias their child's reaction to the test displays. The test trials were delivered in the same way as the habituation trials. Each infant watched two test trials: a Congruent Action and an Incongruent Action event (see Fig. 2). For half of the infants the first test trial was a Congruent Action display followed by an Incongruent Action event, while the other half received the same stimuli in the opposite order. The experimenter was blind to the order in which the two test stimuli were presented. In order to ensure that the dishabituation scores reflected the infants' reaction to the nature of the stimulus event, we had to make sure that they had a chance to identify which kind of event was presented to them. Therefore, since the difference between the two test events could not have been detected earlier than 4 s within the trial, we excluded from the analysis all the infants who watched either of the test trials for less than 4.0 s.

2.2. Results and discussion

The average number of completed habituation trials was 7.14 in the experimental group, 7.35 in the control group among the 12-month-old infants (no significant difference between them), and 7.10 among the 9-month-olds. Fig. 3 represents the looking times during Experiment 1. Although the infants in the 12-month-old control group appear to have shorter looking times during habituation than the infants in the 12-month-old experimental group, this difference is not significant either on the first three or on the last three trials. Nine-month-olds also looked less during the habituation phase than did the 12-month-olds and this difference approached significance during the last three habituation trials [$t(54) = 1.874$, $p < .07$].

The mean looking times during the test phase were analyzed by ANOVAs using event type (congruent vs. incongruent) as a within-subject factor, and order (congruent first vs. incongruent first) and condition (experimental vs. control among the 12-month-olds) as between-subject factors. Initial analyses did not reveal any main effect of, or interaction with, stimulus order, so we omitted this factor from the further analyses. In a two-way ANOVA for the 12-month-olds, the total looking times during the test phase resulted in a significant main effect of condition [$F(1, 54) = 12.765$, $p < .001$], indicating that the experimental group looked longer at the test events that did the control group. Furthermore, this analysis revealed a significant main effect of event type [$F(1, 54) = 4.32$, $p < .05$], indicating longer looking times to the incongruent event. We also performed separate one-way analyses for the experimental and the control groups. These yielded a significant effect for the experimental group [$t(27) = 2.24$, $p < .05$, two-tailed], but not for the control group [$t(27) = 0.601$, $p > .5$, two-tailed]. These

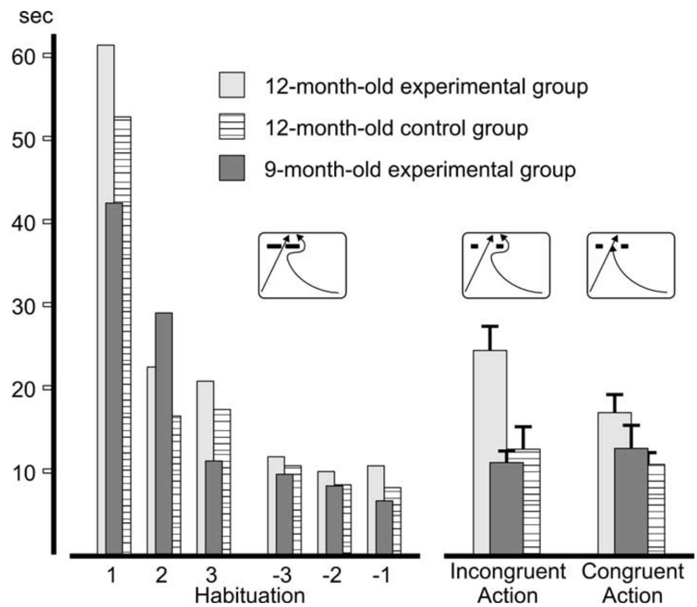

Fig. 3. Mean looking times in Experiment 1. Error bars indicate standard errors.

effects were also confirmed by non-parametric Wilcoxon tests, which indicated a significant difference in looking time for the experimental group ($z = 2.141$, $p < .05$) but not for the control group ($z = 0.444$, $p > .5$).

These results are consistent with the hypothesis that 12-month-old infants can attribute goals that they have not seen achieved. If they had not attributed a goal to the chaser, they would not have had any basis on which to expect it to perform a different behavior in the altered environment of the test events. This expectation could not have been formed on the basis of motion parameters alone, because these were the same in the experimental and the control conditions. The only difference between these conditions was the size of the chaser. However, it is unlikely that infants would be more inclined to attribute goals to bigger than to smaller objects. Rather, we suggest that our 12-month-olds evaluated the chaser's behavior towards the hypothesized goal state of catching the chasee in terms of the relative effectiveness of the action and arrived at the conclusion that the big object's detour (experimental condition) was justified by the constraints of the physical environment (as it was too big to be able to pass through the gap), while the small object's detour (control condition) was not (as it could have passed through the gap). Our conclusion that the two groups interpreted the habituation events differently was also supported by the fact that infants in the experimental condition dishabituated significantly to both test events [$t(27) = 2.85$ and 4.85 for the Congruent Action and Incongruent Action events, respectively, $p < .01$ for both] while infants in the control condition did not [$t(27) = 1.1$ and 1.6, respectively, $p > .1$ for both]. When an action is interpreted as goal-directed, a change in the environment may be relevant and must therefore be evaluated, while the corresponding change has no relevance if the event has not received a teleological interpretation.

To compare the looking times between the two age groups in the experimental condition, we entered the looking times to the test events into ANOVAs. A two-way ANOVA revealed a significant main effect of age group [$F(1, 54) = 12.248$, $p < .001$], indicating longer looking in the older group, and a significant interaction between age group and test event [$F(1, 54) = 4.084$, $p < .05$]. Neither parametric nor non-parametric tests indicated significant differences between the looking times to the two test events in the 9-month-old group. These results indicate that, unlike the 12-month-old participants, the 9-month-olds failed to attribute a goal to the chaser. This conclusion is further supported by the fact that they did not even dishabituate significantly to the test events [$t(27) = 1.66$ and 1.92 to the Congruent Action and Incongruent Action events, respectively, $p > .05$ for both]. Previously we demonstrated that 9-month-olds can form expectations about goal-directed actions of an object in a changed environment when they had a chance to observe the goal state being attained (Csibra et al., 1999). Thus, their failure in the present study is likely to be due to an inability to attribute a non-visible goal, rather than to lacking the capacity to use the goal to predict new actions. It seems therefore that although 9-month-olds can evaluate whether an action is justified by a goal state, they need perceptual evidence about the goal to perform this evaluation. We shall return to the question of the nature of this developmental change between 9 and 12 months of age in Section 4.

The results of this experiment indicated that 12-month-olds could attribute goals that they had not seen achieved. This conclusion was based on the reasoning that they developed expectations about how an object ought to alter its behavior in a new situation, if its observed behavior in the original situation enabled an interpretation of it as a rational goal-approach. Nevertheless, this experiment did not test directly *what* goal was attributed to the action. To answer this question, we ran a follow-up experiment with the same habituation stimuli.

3. Experiment 1A

In this experiment we presented infants with the same habituation events as in Experiment 1. However, in the test events, instead of changing the physical environment, we confronted them with two different "endings" of the same story. One of them was compatible with the goal that could have been inferred from the habituation event, the other was incompatible with it. If infants attribute a specific goal state to the action they observe, their expectation should be violated when the same action does not end with that specific goal state. Since the aim of this study was only to clarify the interpretation of Experiment 1, we did not include further control conditions and we ran it only with 12-month-old infants.

3.1. Method

3.1.1. Participants

Twenty-four 12-month-old infants (11 males and 13 females, mean age = 368.8 days, SD = 8.1 days, range 353–381 days) participated in the study. An additional eight infants were also tested but were excluded from the data analysis because of fussiness (3), failing to habituate (1) or short looking times (4 infants, see Section 3.1.4) during the test trials. All the infants were healthy, full-term infants living in the Greater London area recruited through advertisements.

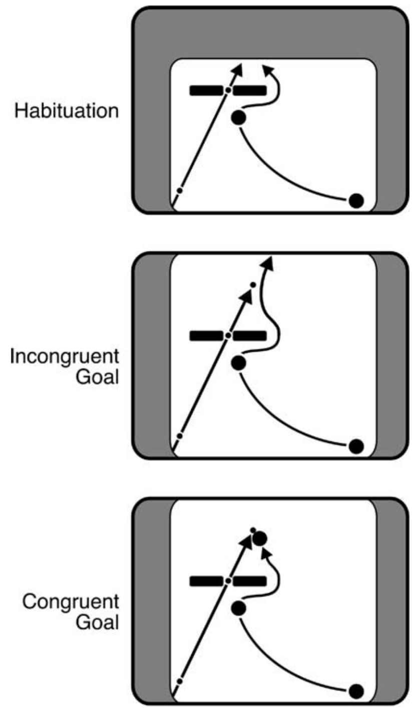

Fig. 4. Schematic representation of the animations used in Experiment 1A.

3.1.2. Apparatus

We used the same apparatus as in Experiment 1 with the only difference that the monitor was replaced by a larger, 29 cm × 38 cm monitor.

3.1.3. Stimuli

The habituation event was the same as the habituation event for the experimental condition in Experiment 1. It was presented in the same size as in Experiment 1, but the presentation rectangle was placed at the lower part of the big screen (see Fig. 4). The other parts of the screen remained black during presentation.

In the test phase of the study, the upper middle part of the screen turned into the same green color as the background of the habituation event, as if a previously hidden part of the scene became now visible. The infants were presented with two test events. During the first part of these events (while the characters remained in the lower part of the scene that had been visible during habituation) the characters behaved exactly the same way as before; thus the two test events represented two alternative outcomes of the already familiar actions. In both events, the chasee stopped shortly after it left the previously visible part of the screen. In the Congruent Goal test event the chaser continued to approach the chasee and stopped as soon as it made contact with the chasee. In the Incongruent Goal test event the chaser modified its path when the chasee stopped, traveled past it, and left the screen. In both test events, the visible objects disappeared 1.5 s after the chasee stopped, and the event was repeated again following a pause of 1 s.

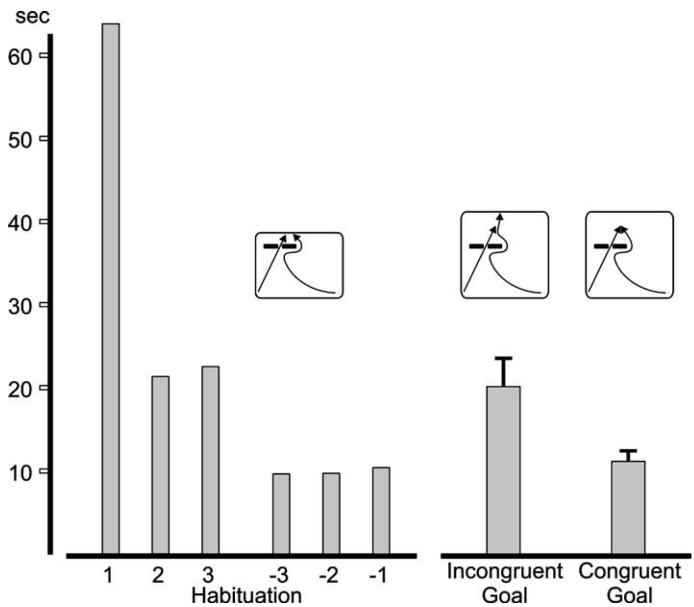

Fig. 5. Mean looking times in Experiment 1A. Error bars indicate standard errors.

3.1.4. Procedure

The procedure was the same as in Experiment 1, but the exclusion criterion for short looking during the test trials was increased to 6.0 s.

3.2. Results and discussion

Infants completed the habituation criterion in an average of 7.25 trials. Fig. 5 shows the average looking times during both the habituation and the test phases. A two-way ANOVA with event type (congruent vs. incongruent) as a within-subject factor and test trial order (congruent first vs. incongruent first) as a between-subject factor revealed only a significant main effect of event type [$F(1, 22) = 4.919$, $p < .05$]. This effect was due to the fact that infants looked longer at the Incongruent Goal test event than at the Congruent Goal test event. We also tested whether the attention of our participants recovered at all during the test events. We compared the looking times during the test events to the mean looking times during the last three habituation trials in paired *t*-tests. These tests indicated that the infants did not dishabituate to the Congruent Goal test event [$t(23) = 0.955$, $p > .3$] but they did dishabituate to the Incongruent Goal test event [$t(23) = 2.827$, $p < .01$].

These results indicate that, during the habituation phase, infants successfully inferred what might have happened after the two figures had left the screen. They found the Congruent Goal test event, where the chaser caught up with, contacted and stopped next to the chasee, compatible with their expectation. In contrast, they apparently found the Incongruent Goal test event, in which the chaser passed by the chasee and left the screen, unexpected. This pattern of results is consistent with attributing to the chaser the goal of catching or coming to contact with the chasee. Note that the infants did not see this goal achieved during habituation, hence they had to infer it from the chaser's behavior. Therefore, this result provides clear evidence that 12-month-olds can attribute a goal that they have not seen achieved.

Note also that some lower-level alternative explanations, which at first may seem plausible, do not apply. One may say, for example, that infants simply learnt from observing the chasing event that the distance between the moving objects tend to decrease and the Incongruent Goal event would have violated this expectation. However, in our habituation event (see Fig. 4) there was a phase during the detour action when the actual distance between the moving objects increased rather than decreased. Another explanation could suggest that the chaser kept moving longer in the Incongruent Goal event than in the Congruent Goal event and this difference in relative amount of movement might have made the former display inherently more interesting. Note, however, that it is unlikely that a half second difference in the amount of movement perceived could have accounted for an average of 10 s looking time difference found between the two test displays. Moreover, this was a habituation study, and the above difference in amount of movement was likely to be counterbalanced by the fact that the Congruent Goal event was more dissimilar to the habituation event than the Incongruent Goal event. While both objects left the screen during habituation, one object stayed and one left in the Incongruent Goal event, but both objects remained present in the Congruent Goal event.

In sum: Experiments 1 and 1A together demonstrated that (1) 12-month-olds can infer a non-visible goal from an observed incomplete action, (2) this inference is based on the assumption that the action is rational in relation to some goal state, (3) the inferred goal is specific enough to allow evaluation of the observed end-state as matching the inferred goal or not (Experiment 1A), and (4) the inferred goal allows predictions to be made about what new action ought to be performed as means towards the same goal in an altered environment (Experiment 1).

4. Experiment 2

When people observe and try to make sense of other people's actions, they invoke not only inferred goals (imperceptible states that take place in the future), but sometimes also inferred states of affairs of the physical world that are imperceptible for them for some reason. For example, if we see someone placing a box gently and carefully on the table, we may infer that there is something precious and breakable in the box. Or if we see someone running towards a bus stop at the other side of the corner, we infer that a bus is waiting there or approaching the location, even if we cannot see it. Note that often we do not have any other evidence for these inferred states of affairs than the behavior of the person that we observe. In making these inferences we are relying on the same assumption as in goal-attribution: that the observed action is rational in relation to a goal state, and we complete the imperceptible parts of the world by inference so that they justify the action as rational. Note that these are non-demonstrative inferences; they do not have to be true (and sometimes they are false, indeed). However, by justifying the observed action they help us interpret the behavior as a rational means towards some goal.

We are not aware of any direct evidence that would show that infants can draw these kinds of inferences from observed actions. There are indications that 1-year-old and even younger infants can infer the numerosity of objects at occluded parts of space (e.g., Wilcox, 1999; Xu & Carey, 1996) or can infer the presence of hidden objects (Baillargeon, 1994). These inferences, however, are drawn on the basis of featural individuation processes or physical constraints, and not on the basis of action interpretation and the rationality principle.

In Experiment 2, we tested whether infants can infer the presence of an occluded physical object in order to justify the observed action of an animated figure. The habituation event was similar to the one we used in Gergely et al. (1995), where an animated figure approached a goal object by jumping over an obstacle. The present habituation event differed from this only in two respects: we (1) made the animation three dimensional and (2) occluded the part of the space that the acting object jumped over. In the test phase, the occluder was removed and it either revealed an object or an empty space. If infants justify the observed jumping action by inferring the presence of an obstacle behind the occluder, seeing the obstacle would confirm, while seeing the empty space would violate their expectation, which should be reflected in longer looking time in the latter case.

4.1. Method

4.1.1. Participants

Sixteen 12-month-old (7 males and 9 females, mean age = 366.3 days, *SD* = 8.0 days, range 352–380 days) and sixteen 9-month-old (7 males and 9 females, mean age = 278.6 days, *SD* = 6.0 days, range 271–297 days) infants participated in the study. An additional eight 12-month-old and seven 9-month-old infants were also tested but were excluded from the data analysis because of fussiness (1 and 2), experimenter error (2 and 1) or too short looking times (see Section 4.1.4) during the test trials (five 12-month-olds and four 9-month-olds). An additional 16 12-month-olds (8 males and 8 females, mean age = 370.5 days, *SD* = 7.6 days, range 358–387 days) were also recruited for the baseline condition. All the infants were healthy, full-term infants who were recruited through advertisements in local Hungarian magazines.

4.1.2. Apparatus

The infants sat in their parent's lap in a darkened experimental room looking at the monitor placed at eye level from a distance of 1 m. The 18 cm × 24 cm color computer monitor appeared in a window cut on a large black occluding screen, which made sure that the child's attention was not drawn to other objects in the room. A small, computer-controlled speaker was placed on the monitor for the presentation of tones in order to get the infant's attention. A video camera focusing on the subject's face was located below the monitor. Its lens peeped through an opening cut in the screen 25 cm below the subject's eye level. This allowed the experimenter to monitor the subject's eye fixations on a TV monitor from a separate room. From there she also controlled the stimulus presentation and registered the looking times by operating the keyboard of two personal computers.

4.1.3. Stimuli

The stimuli were computer-animated visual events modeled after the stimuli in Gergely et al. (1995) and created by a 3D animation software. The habituation event (Fig. 6A) started

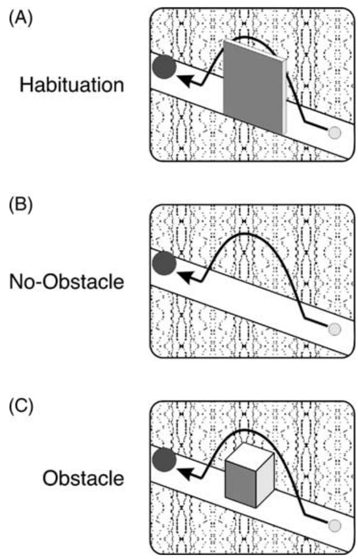

Fig. 6. Schematic representation of the animations used in Experiment 2.

with the simultaneous appearance of two balls (a small red and a larger yellow ball) at the two sides of a "mountain path." The path appeared to be a horizontal plane bordered by a vertical hillside behind and a vertical cliff below. This arrangement was intended to make clear that no other route than the path was available between the balls. There was a black thin "wall" occluding the middle section of the path between the two balls. First, the large ball expanded, then it contracted (regaining its original shape). This was immediately reciprocated by the same action carried out by the small ball. This "exchange" was then repeated a second time, which took all together 3 s. After this the small ball started to move towards the large one along the path, then it jumped over the area behind the occluder, landed in front of the large ball, continued its approach horizontally until the two balls made contact. The jumping action followed a parabolic trajectory and the small ball was visible at the beginning, at the middle and at the landing phase of the jump, while it was hidden momentarily twice while behind the occluder (see Fig. 6A). The duration of the whole movement was 3.5 s. Upon contact the two balls repeated their reciprocal expansion–contraction routine again. The whole event lasted 10 s, then the figures disappeared from the screen. After a 1 s break the habituation event started again.

The two test events started with the same display as the habituation event. However, after the appearance of the two balls and the occluder, the occluder was raised upward vertically until it left the screen, thus revealing the space behind it. This phase lasted 3 s. In the No-Obstacle test event (Fig. 6B) the path was empty, while in the Obstacle test event (Fig. 6C) a cube became visible that was blocking the path between the two balls. The behavior of the two balls during the test events was identical to that in the habituation phase, i.e., after the reciprocal expansion–contraction routine the small ball performed the jumping action. In the Obstacle test event the jumping action took place over the cube, while in the

No-Obstacle test event the space over which the small ball jumped was empty. Both test events lasted 13 s.

4.1.4. Procedure

For the experimental groups the procedure was the same as in Experiment 1 with the difference that the exclusion criterion for too short looking during the test events was 10 s. (This amount of fixation was minimally necessary to apprehend the full structure of the test event.) The infants in the baseline condition were presented only with the two test events, which they watched as long as they wished. A trial was terminated when the infant looked away from the screen for more then 2 s. Half of the participants in the baseline condition watched the Obstacle test event first, the other half watched the No-Obstacle event first.

4.2. Results and discussion

The average number of trials needed to reach the habituation criterion was 6.1 for the 12-month-olds and 6.7 for the 9-month-olds. This difference was not significant [$t(30) = 1.524$, $p > .1$]. There were no significant differences in the average looking times for either the first or the last three trials of the habituation phase between the age groups. Fig. 7 represents the average looking times in Experiment 2.

We analyzed the mean looking times of the experimental groups during the test phase in a three-way ANOVA in which event type (Obstacle vs. No-Obstacle) served as a within-subject factor and age group (9- vs. 12-month-olds) and presentation order (Obstacle first vs. No-Obstacle first) served as between-subject factors. This analysis revealed a main effect of age group, indicating that 9-month-olds looked longer at the test events than 12-month-olds. We therefore analyzed the two age groups in separate ANOVAs. In the 12-month-old group this

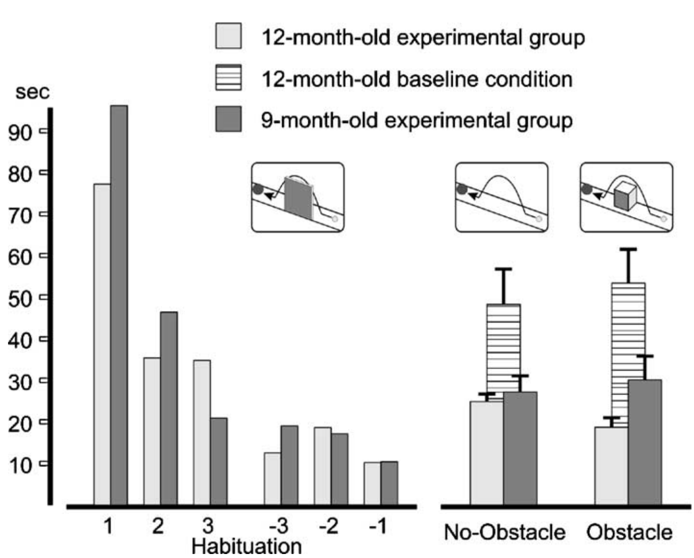

Fig. 7. Mean looking times in Experiment 2. Error bars indicate standard errors.

analysis resulted a significant effect of event type [$F(1, 14) = 10.458$, $p < .01$] indicating longer looking times for the No-Obstacle event. No other effect was significant. A similar two-way ANOVA performed for the 9-month-olds revealed only a significant effect of order [$F(1, 14) = 4.843$, $p < .05$], indicating that those infants who saw the No-Obstacle event first and the Obstacle event second looked longer at the test events than those infants who saw the test events in the opposite order. (This effect was unexpected and we do not have an explanation for it.)

The above results suggest that the 12-month-olds, but not the 9-month-olds inferred the presence of an obstacle behind the occluder in the habituation event. This conclusion was also corroborated by non-parametric tests, which showed that 12-month-olds tended to look longer at the No-Obstacle than at the Obstacle event (Wilcoxon $z = 2.275$, $p < .05$), while in 9-month-olds no such difference was found (Wilcoxon $z = 0.103$, $p > .5$).

A two-way ANOVA on looking times in the baseline condition did not reveal a significant main effect of either the event type or the order factor. However, there was a significant interaction between event type and order [$F(1, 14) = 4.790$, $p < .05$], indicating that the infants looked longer at the first test event regardless of its type. This is, of course, expected as these infants had not been habituated to the stimuli. For the same reason, the looking times to these events were much longer in the baseline condition than the looking times produced by the experimental groups (see Fig. 7). The absence of an event type main effect in the baseline group indicates that the differential looking times in the 12-month-old experimental group cannot be attributed simply to the stimulus differences inherent in the test events: rather, they must have been based on the differential interpretation that the infants developed during watching the habituation event.

And this interpretation agrees well with our adult intuition. Why would the small ball jump in the air while traveling towards the large ball, if there was no obstacle in its way? We infer an obstacle behind the occluder to make sense of the ball's jumping behavior. We suggest that the infants' looking time pattern in this experiment reflects the functioning of the same intuition. This intuition is based on the same rationality principle that allowed the 12-month-olds in Experiments 1 and 1A to attribute unseen goals to objects and predict their behavior accordingly. Note that the absence of the obstacle in the No-Obstacle condition does not violate our physical knowledge; it does not *have to be* there. But its absence violates our expectation that the object approaches its goal effectively (in other words, in a rational manner) and questions the interpretation that the action is performed in order to achieve an end, i.e., that it is a goal-directed action.

The 9-month-olds did not display the same looking pattern as did the 12-month-olds in this experiment. This is interesting because our earlier studies using a similar jumping event have indicated that infants at this age can already evaluate the rationality of actions and can interpret them as directed to goal-states (Csibra et al., 1999). However, in our earlier studies the physical constraint that justified the ball's jumping approach (i.e., the presence of the obstacle) was always *visible*, while in the current study it had to be inferred as the area over which the jumping action took place was occluded from the infants' view. Thus, it seems that the 9-month-olds' failure to interpret the jumping approach as a goal-directed action has to do with the lack of direct perceptual evidence about the physical constraints that would allow the evaluation of the action's effectiveness. Furthermore, it is unlikely that their failure would originate from some lower-level limitation, such as an inability to interpret the perceived actions in three dimensions. Infants older than 6 months of age have been shown to be able to recover depth and occlusion information from both monocular depth cues (e.g., Arterberry, Bensen, & Yonas, 1991) and motion cues (e.g., Csibra, 2001). We shall discuss the nature of the developmental change between 9 and 12 months of age in Section 5.

5. General discussion

We developed a theoretical model to account for infants' ability to interpret observed behaviors as goal-directed actions. This model claims that a goal-directed action is represented as a well-formed teleological representation of three elements: the goal state, the action as the means to the goal state, and the relevant aspects of reality as constraints on possible actions. In this representation the criterion for well-formedness is provided by the principle of rational action: the action must be seen as an effective means to bring about the goal state within the constraints of reality. This model led us to the predictions that, if infants represent goal-directed actions in this manner, they should be able to infer unseen goals or unseen reality constraints whenever the other two elements of the teleological representation are available to them.

Our results confirmed these predictions, at least for 12-month-old infants. Experiments 1 and 1A have demonstrated that 12-month-olds can interpret an action as goal-directed even if they have not seen the goal achieved. Note that this age is much younger than the age at which the same ability has been demonstrated in studies using the imitation paradigm (Meltzoff, 1995; see also Bellagamba & Tomasello, 1999). Experiment 2 has shown that 12-month-olds can infer the presence of an unseen object to justify an observed action as goal-directed. We believe that this is the first demonstration that infants at such an early age can use a non-physical principle (namely, the rationality principle) to infer some physical aspects of the world.

We have provided evidence that 1-year-old infants use the rationality principle productively. But how does this productive inferential process actually work? How can one infer the presence of an object from observing an action? Deductive inference could not work here, because there are no causal laws that would make the presence of an obstacle necessary when someone performs a jumping action. We suggest that these inferences, like other inductive inferences, involve two processes: hypothesis formation and verification. The hypothesis formation phase fills the missing element (the goal or the reali ty constraints) in the three-place representational schema with some hypothetical state of affairs, while the verification process checks whether the new element would satisfy the well-formedness criterion (the rationality principle) of the teleological schema. If the verification process judges the representation as well-formed, the hypothetical state is inferred to be actual (i.e., the hypothetical end-state is attributed as a goal or the hypothetical physical constraints are taken as real). If the verification process fails, the search for an alternative suitable hypothetical state of affairs may continue. Note that while this verification process relies on a specific principle, the actual hypotheses may be generated in several different ways: through learned associations (agents usually jump over something), through social understanding (agents often like to be close to each other), or through simulation (what would I do if I had a similar goal in a similar situation?).

Turning to the developmental question: we hypothesize that the 9-month-olds' failure in our tasks is probably due to the insufficiency of hypothesis formation processes, rather than to an inability to perform the verification of the well-formedness of teleological representations. This is suggested by our earlier findings (Csibra et al., 1999) showing that infants at the same age could set-up a teleological representation (hence verify its well-formedness) in situations where information about all the three elements of the schema were perceptually available, and were able to use this representation for action prediction. The inability of 9-month-olds to generate appropriate hypotheses in situations where no direct perceptual evidence is available may be attributable either to the weakness of the background processes (association, social understanding, simulation, etc.) that provide the content of the hypotheses, or to a domain-general limitation in representing hypothetical states of affairs. The first possibility emphasizes that a certain amount of accumulated background knowledge may be necessary to generate such contents for hypothesis formation that can satisfy the well-formedness conditions on teleological action representations, and that 9-month-olds may not yet possess sufficient background knowledge to achieve this purpose. In contrast, the second alternative implies a general immaturity of the developing cognitive system that prevents it from generating representations of hypothetical states of affairs. Our studies and the available evidence from other experiments do not allow us at present to choose between these possibilities, though we tend to believe that it is the lack of relevant experience, rather than cognitive immaturity, that prevents 9-month-olds from generating well-formed teleological explanations on the basis of partial information. Either way, the development between 9 and 12 months of age that enables the older infants to infer hypothetical goals and reality constraints involves changes in processes that are external to the core representational ability to interpret observed actions in terms of teleological representations.

We would like to emphasize that the principle of rational action, in the sense we use this term, is not a type of *knowledge* about certain entities of a specific domain, rather it expresses an abstract *well-formedness constraint* over action representations. As such, it can be applied to knowledge specific to different domains and it always operates on representations formed in those particular domains. In situations, as in the present studies, where the goal is defined in terms of a (moving or stationary) spatial referent, the criterion of satisfying the rationality principle can simply be "the shortest available pathway toward the goal." In our experiments, to evaluate the effectiveness of the agents' path to the goal, infants had to rely on their physical and geometrical knowledge about object motion. They had to understand, for example, that solid objects are impenetrable and therefore other objects cannot pass through them (cf. the solidity principle, Spelke, 1994). In Experiments 1 and 1A they also had to be able to assess the relative relation between agent size and gap width. There is no doubt, however, that 9-month-olds already possess the necessary physical knowledge required for these evaluations (Baillargeon, Kotovsky, & Needham, 1995; Spelke, Breinlinger, Macomber, & Jacobson, 1992). But note that physical knowledge itself is not sufficient in these situations. Although the criterion of "shortest pathway" is evaluated within the domain of physics, there is no physical principle that requires that objects should follow the "shortest pathway" and adjust their path to the changing environment accordingly. Moreover, the notion "shortest path" logically entails a pre-specified end state, which implies that the event should be evaluated not according to its antecedents (causes) but according to its consequences (goals). Therefore, the evaluation of the effectiveness of goal-approach in terms of a "shortest path" criterion involves teleological, rather than causal representations of actions.

One may ask then, why do we call the principle that governs infants' reasoning in these studies the "principle of rational action" instead of the "principle of shortest pathway?" First, note that while in the experiments discussed in this paper the criterion of "shortest path" always applies, there are a number of further studies showing goal-attribution in this age range where this is not the case. In another study of ours, for example, we have pitted against each other two alternative perceptual cues that can be interpreted in terms of amount of exerted effort: "shortest path" versus "squeezing through a narrow gap" (Csibra & Gergely, 1998b). The results demonstrated that under certain circumstances the latter cue wins out in determining the evaluation of the effectiveness of the goal-approach over the cue of "shortest pathway." Another kind of example where "shortest path" will not do as the criterion for well-formedness is provided by the Woodward and Sommerville (2000) study that we cited in Section 1, which demonstrated that infants attribute goals only if the actions leading to the end state do not include unnecessary steps. Similarly, ingenious experiments by Onishi (2001) confirmed that actions (removing obstacles) that make a target object accessible to a hand are interpreted as goal-directed by 10-month-old infants, but the same actions do not lead to goal-attribution if they are not justified by the relative positions of the obstacles and the target object. Reasoning in these cases does not rely on a "shortest pathway" principle but on a more abstract "efficiency" principle and fits perfectly the characterization of teleological action representations that we propose. Furthermore, not only looking time studies show that infants tend to interpret observed actions in terms of their apparent rationality. Recently, Gergely, Bekkering, and Király (2002) provided evidence that infants modulate their imitative behavior according to the justifiability of the goal-directed actions performed by a model. These data together suggest that infants' reasoning about actions is not based on the perceptual criterion of "shortest pathway"; rather, they can be formalized in terms of teleological action representations whose well-formedness constraint is provided by the more abstract criterion of the "efficiency" of goal-approach.

Second, there is an even further level of abstraction in adults' mature and mentalistic action interpretations, which is couched in terms of their "theory of mind." At this level, the elements of teleological interpretations are attributed as the contents of intentional mental states to the agents. With this step, goals become "desires," actions become "intentions," and physical constraints become "beliefs." If we applied this mentalistic level of action interpretation to the habituation event in Experiment 1, we would say, for example, that "the ball *wanted* to catch the other ball, *believed* that the gap between the bars was too small for it to pass through, and so it *decided* to take a detour around them." Note that at this level of abstraction the "efficiency" criterion ceases to coincide with the rationality principle because when the latter is applied over the domain of intentional mind states, an action that fulfills the criterion for rationality will not necessarily correspond to the most "efficient" action towards realizing one's goal any more. For example, if someone acts on the basis of a desire (Oedipus wants to avoid fulfilling the prophecy that he will marry his mother) and a false belief (he believes that Jocasta is not his mother), his action (Oedipus marries his mother) may not be an efficient way to achieve his goal, but it will nevertheless be a rational action to fulfill his desire (since it is consistent with his beliefs). In other words, the principle of rational action within the domain of intentional mind states involves the application of the efficiency principle to the representational *contents* embedded within those mental states. We think that there is no positive evidence suggesting that 9- and 12-month-old infants' reasoning operates at this more abstract, mentalistic level, and in the present studies infants can do well just by relying on the simpler, non-mentalistic teleological representations. However, we wish to emphasize that while teleological representations do not contain mental states, the well-formedness criterion (of efficiency) used at this level is basically identical to the rationality principle used in the mentalistic level because the criterion of evaluation used there does not apply to the mental states themselves but only to their representational contents.

A further corollary of the fact that the rationality principle is a well-formedness constraint that can apply to different domains of knowledge is that it does not necessarily involve *a priori* criteria of application. Many theorists suggested that goal-attribution might be innately restricted to objects exhibiting certain behavioral characteristics, primarily self-propelled motion (Carey & Spelke, 1994; Leslie, 1994; Premack, 1990), human features and biomechanical movement (Meltzoff, 1995), or contingent reactivity at a distance (Johnson, Slaughter, & Carey, 1998). This hypothesis was disconfirmed by our earlier studies (Csibra et al., 1999) that indicated that neither of these cues is necessary for goal-attribution to occur. This is not to deny the possibility that the presence of some of these cues may make it more likely that an agent's behavior receives a teleological interpretation (Gergely & Csibra, in preparation). What cues can then infants use to decide whether an observed event is to be explained in teleological terms? It is possible that there are, in fact, no such pre-specified cues and that it is the applicability of the efficiency principle that defines the extension of the concept of "goal-directed agent." This view suggests that early cognitive development can partly be characterized by a learning process that associates various observable cues with the success of applying already existing explanatory modes of construal (cf. Keil, 1995). On the other hand, behavioral cues, such as contingent adjustment to environmental change (cf. Mandler, 1992), or equifinality of actions (cf. Heider, 1958), can be derived from the principle of rational action itself. More systematic research is necessary to establish whether either of these or some other cues play a role in triggering a teleological interpretation of action events.

In sum, our studies demonstrated that, relying on an abstract teleological representation, 1-year-olds can infer unseen goals and the presence of unseen objects from observed actions. We argued that these inferences may be achieved by applying the criterion of efficiency without ascribing intentional mental states such as desires or beliefs to the agents. At the same time, we have suggested that this emerging capacity for teleological interpretations of actions by 1 year of age constitutes an important developmental step towards more mature action interpretations in terms of attributed intentional mind states especially in view of the fact that these two levels involve the same principle for evaluating rational action.

Note

1. Note that while Dennett's and our use of the term "rationality" rely on the same general intuition, there are also some differences in his and our way of applying this construct. For Dennett (1987), rationality is a pre-theoretical concept that is an inherent part of the intentional stance, while we—applying it in the context of early understanding goal-directed

spatial actions—operationalize it as the effectiveness of the goal-approach. Thus, while for Dennett the rationality assumption is an attribute of the intentional stance, for us it also applies to the teleological stance that, arguably, does not yet involve representing and attributing intentional mental states to the actor's mind (Csibra & Gergely, 1998a). Nevertheless, it should be clear that both approaches share the emphasis that everyday practical reasoning about actions needs to be based on the assumption of rationality.

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