Journal of Experimental Child Psychology 204 (2021) 105035

Contents lists available at ScienceDirect

Journal of Experimental Child Psychology

journal homepage: www.elsevier.com/locate/jecp

Children's reasoning about the efficiency of others' actions: The development of rational action prediction

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ARTICLE INFO

Article history:
Received 27 February 2020
Revised 12 October 2020
12 October 2020

Keywords:
Rational action prediction
Efficiency
Goal understanding
Reasoning
Action anticipation
Teleological stance

ABSTRACT

The relative efficiency of an action is a central criterion in action control and can be used to predict others' behavior. Yet, it is unclear when the ability to predict on and reason about the efficiency of others' actions develops. In three main and two follow-up studies, 3- to 6-year-old children (n = 242) were confronted with vignettes in which protagonists could take a short (efficient) path or a long path. Children predicted which path the protagonist would take and why the protagonist would take a specific path. The 3-year-olds did not take efficiency into account when making decisions even when there was an explicit goal, the task was simplified and made more salient, and children were questioned after exposure to the agent's action. Four years is a transition age for rational action prediction, and the 5-year-olds reasoned on the efficiency of actions before relying on them to predict others' behavior. Results are discussed within a representational redescription account.

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https://doi.org/10.1016/j.jecp.2020.105035
0022-0965/

Introduction

Humans are not merely passive perceivers of other people's behavior but rather have active expectations about how others' actions unfold over time. Importantly, this is not only true for adults (Clark, 2013; Falck-Ytter, 2012; Fogassi et al., 2005); even young children predict other people's future behavior (e.g., Boseovski, Chiu, & Marcovitch, 2013; Clement, Bernard, & Kaufmann, 2011; Grant & Mills, 2011; Poulin-Dubois, Brooker, & Chow, 2009). Infants attend to various characteristics of others' actions (for a review, see Gredebäck & Daum, 2015), segment the stream of others' actions into meaningful events (Friend & Pace, 2011; Pace, Carver, & Friend, 2013), and detect the failure of others' behavior (Brandone & Wellman, 2009). Besides this, more complex abilities and a more differentiated understanding of human behavior seem to develop, based on these earlier competences, through the preschool years (Clement et al., 2011). Children's perception and prediction of others' behavior is related to their social competence (Slaughter, Imuta, Peterson, & Henry, 2015), and their capacity to predict others' actions develops profoundly over the preschool years (Monroy, Gerson, & Hunnius, 2017; Schuwerk & Paulus, 2016). Consequently, the ontogenetic origins and early development of action prediction is a topic of vivid discussion in developmental psychology.

Rational action: Children's appreciation of the efficiency of others' actions

One key question concerns at what age and to what extent children take the efficiency of actions into account when predicting another's future behavior. Research on humans' own action control has demonstrated that people tend to choose actions based on their relative efficiency (e.g., Bernstein, 1967; Rosenbaum, Chapman, Weigelt, Weiss, & van der Wel, 2012). This ability for efficient action selection emerges during the first years of life (Jovanovic & Schwarzer, 2011; McCarty, Clifton, & Collard, 1999) and develops strongly during the preschool years (Thibaut & Toussaint, 2010; Weigelt & Schack, 2010). However, successfully predicting the future course of others' behavior requires taking the relative efficiencies of the available action alternatives into account. Thus, learning that humans act efficiently is difficult. Moreover, not all humans act consistently efficient, and not all actions are subject to considerations of efficiency. Although efficiency considerations are one factor in action selection, human behavior is also guided by rules and norms that rarely rest on mere efficiency considerations (e.g., not taking the direct way across the street but rather looking for a crosswalk). Indeed, many of our actions are guided by historically transmitted routines (Weber, 1978). Consequently, many factors play a role for understanding and predicting others' behavior (Clement et al., 2011). Thus, it is interesting to explore when and how children become able to consider the efficiency of others' actions, that is, when they start to engage in *rational action prediction.*

Interestingly, there has been a debate within the field of infancy research on whether young infants already have an implicit assumption that others will *act efficiently.* One line of research mainly relied on habituation-based measures (Gergely, Nadasdy, Csibra, & Bíró, 1995; Gredebäck & Melinder, 2010; Skerry, Carey, & Spelke, 2013; Sodian, Schoeppner, & Metz, 2004) and imitation-based measures (Gergely, Bekkering, & Kiraly, 2002) in order to *retrospectively* assess children's expectations. Based on these studies, the *teleological stance theory* suggests that preverbal infants understand and evaluate others' actions on the basis of the assumptions that others act efficiently (Gergely & Csibra, 2003). This has also been referred to as *rational action.* In other words, the teleological stance theory assumes that "(1) actions function to bring about future goal states, and (2) goal states are realized by the most rational action available to the actor within the constraints of the situation" (Gergely & Csibra, 2003, p. 289). For example, assessing infants' anticipatory gaze, Bíró (2013) suggested that infants anticipate the agent to take the shortest path if the agent's goal is clear and if infants know about the situational circumstances. In other words, it has been proposed that infants anticipate actions that are more efficient, and their results are affected from the saliency of the goal. Yet, these findings have been contested and alternative interpretations have been provided (e.g., Beisert et al., 2012; Paulus, 2012; Paulus, Hunnius, van Wijngaard, et al., 2011). Indeed, to date there is a heated debate on the developmental emergence of children's ability to consider the efficiency of others' actions (Juvrud & Gredebäck, 2020; Király & Oláh, 2020), calling for further empirical investigation.

Moreover, given that previous research focused largely on *implicit measures* such as action anticipation, little is known about whether preschool children consider an action's efficiency in their explicit predictions. Note that *action anticipation* is here defined as the visual anticipation on the future course of an action or the retrospectively assessed expectations about others' actions (Gredebäck & Daum, 2015), whereas *explicit action prediction* refers to behavioral and verbal predictions and verbal reasoning about others' behavior. Because the current research focused on whether young children consider another's action efficiency in their explicit predictions, we use the term *rational action prediction* henceforth.

This lack of knowledge is particularly unfortunate given the ongoing debate on whether or not, and to what extent, infants actually consider the efficiency of others' actions. Knowledge on the ontogeny of rational action prediction could contribute to the debate how a full appreciation of efficiency of others' actions emerges in development. Notably, it is well established that adults engage in rational action prediction (e.g., Baker, Saxe, & Tenenbaum, 2009). However, to our knowledge, there is only one study that included a developmental sample. Schuwerk and Paulus (2016) presented 5-year-old children with an agent who wanted to reach a goal. Two paths led to the goal; one was short and the other was long. The 5-year-olds visually anticipated that an agent would use the shorter of two paths to reach a goal. Thus, by 5 years of age, children anticipated that an agent uses a more efficient path to reach a goal. Yet, it is unclear how children reasoned about the two paths, that is, to what extent they could justify their prediction with respect to the action's efficiency. Moreover, the study did not examine the early development of rational action and mainly focused on the *action anticipation* based on gaze patterns. Thus, it is an open question whether preschool children consider efficiency at the action level (e.g., selecting the most efficient action in their predictions) and reason about the efficiency of others' actions and when it emerges. More specifically, it could be essential to have deeper knowledge on the development of rational action prediction for two main theoretical reasons.

First, if we were to find a developmental décalage between implicit measures (e.g., action anticipation) and explicit measures (e.g., action prediction, reasoning) of rational action processing, this would speak to recent debates on the nature of early social cognition. In particular, it would suggest that the theoretical debate about two systems of early social cognition (Apperly & Butterfill, 2009) should not be restricted to the theory-of-mind (ToM) domain but also needs to be extended to the development of teleological reasoning. Second, it has been argued that explicit reasoning about others' actions is not merely epiphenomenal with respect to a potential implicit understanding of others' behavior. Explicit reasoning (i.e., verbal responding to verbal questions) relates to an understanding (and potential explication) of the reasons for an action (Perner & Roessler, 2012). Such an understanding is the basis for an intersubjective exchange of reasons for and an evaluation of these claims and therefore is the basis of complex forms of intersubjectivity (cf. Brandom, 1994). In this context, it is particularly important when we consider the efficiency and rationality of an action. However, as indicated above, it is surprising that little is known about children's ability to reason about the efficiency of others' actions.

Interestingly, this lack of research on the development of the ability to explicitly reason about and make predictions based on the efficiency of others' behavior is quite surprising because in another important area of research on early social cognition, the ToM domain, developmental psychology proceeded in reversed order. Researchers initially examined explicit ToM reasoning during the preschool years (e.g., Ruffman, Slade, & Crowe, 2002; Slaughter, Peterson, & Mackintosh, 2007). Only recently did researchers, motivated by earlier findings of implicit signs of ToM understanding (Clements & Perner, 1994) and a differentiation between implicit and explicit physical reasoning (Hood, Carey, & Prasada, 2000), systematically start to debate whether or not there is an implicit ToM understanding before the explicit one (e.g., Heyes, 2014; Perner & Ruffman, 2005; Ruffman, 2014; for a review, see Sodian, 2011). These findings gave rise to theoretical models that attempted to reconcile the findings of the infant studies with the earlier findings of a developmental onset of ToM during the preschool years (e.g., Apperly & Butterfill, 2009).

Rational action prediction during the preschool years: Representational redescription perspective

Although the measures of rational action can be separated as *implicit* and *explicit,* this differentiation does not answer how implicit and explicit measures correspond to the underlying representations and execution of the resulting actions. Rather than assuming an early developing rational action understanding, alternative theoretical accounts would assume that young children's increasing ability to act efficiently is based on action–perception processes (cf. Bernstein, 1967). In the course of further development, children start to go beyond implicit (perception–action based) representations and notice that actions are conducted efficiently and thus might build cognitive representations of efficiency that allow them to reason about others' behavior. Indeed, the *representational redescription model* proposes that "re-representation" is a recursive and domain-general process recurrently occurring in each microdomain or macrodomain that allows children to generalize knowledge first acquired behaviorally in a given domain. According to this model, young children are mostly data driven at first, and the format of their first representations in development is implicit (Level I). In Level I, representations are procedural and independent and are sequentially constrained. In the following phase, Explicit 1 (E1), the Level I representations are redescribed into an explicit format in which they become manipulable. As a result, "the child can introduce violations to her data-driven, veridical descriptions of the world—violations that allow pretend play, false belief, and the use of counterfactuals" (Karmiloff-Smith, 1992, p. 22). In the following phases, Explicit 2 (E2) and Explicit 3 (E3), representations go through "progressive explicitation" for a given domain are subject to conscious access, theory building, and verbal report (Karmiloff-Smith, 1990, 1992).

In the current research, we relied on a representational redescription framework considering the fact that it goes beyond the basic implicit and explicit dichotomy and suggests a progressive explicitation in any given microdomain (for a similar but extended model, see Dienes & Perner, 1999). Thus, through the progressive explicitation, children can create more abstract and hierarchically complex goal-directed representations with higher control of intentions (see Karmiloff-Smith, 1990, and Zelazo, 2018). At this point, one should also make a distinction between behavioral mastery in efficient behavior selection and the cognitive representation of efficiency. That is, although efficient behavior emerges during the infant and toddler years (e.g., McCarty et al., 1999), this shows a type of behavioral mastery of efficient action without having a cognitive representation of efficiency such as the end-state comfort effect in tool use. In the course of development, these action–perception-bound abilities become subject to representational redescription that might allow for the formation of conceptual understanding of efficient action. In other words, what has been learned on a practical or action level is transferred to the level of conceptual understanding (see also Piaget, 1932). More specifically, in the course of the preschool years, 3- to 6-year-old children develop enhanced capacities to overcome exogenous (situational) factors, which allows them to take control over endogenous representations (Dick, Overton, & Kovacs, 2005; Karmiloff-Smith, 1992). Thus, one could expect a linear development in efficiency consideration in 3- to 6-year-olds' rational action prediction. Such a pattern has been observed in different domains of skills such as drawing (Allen, Nurmsoo, & Freeman, 2016; Karmiloff-Smith, 1990), language (Karmiloff-Smith, 1992), executive function (Zelazo, 2015), complex reasoning (Zelazo & Frye, 1997), and the ability for reflection (Allen & Bickhard, 2018). These results may also indicate that these cognitive processes are not mutually exclusive but rather developmentally interwoven at some points. For instance, developing language abilities may play a major role in redescribing action-related representations in another format. Beyond the teleological stance theory and other models focusing on implicit-to-explicit change, an alternative view that was recently suggested by Juvrud and Gredebäck (2020) based on the embodied account argues that during the first year infants own motor capacities that might inform their rational action prediction later in development. However, in the current research, we did not investigate the possible relation between motor capacities of preschool children in efficient action selection and rational action prediction, so we do not focus on the latter account in the current article.

The current research

Taken together, the current studies aimed at investigating explicit action prediction and explicit reasoning in preschool children's efficiency considerations. Across three main studies and two follow-up studies, we examined the development of explicit action prediction and explicit reasoning about the efficiency of actions in preschool children. Participants were confronted with short vignettes based on previous empirical paradigms (e.g., Bíró, 2013; Schuwerk & Paulus, 2016). We decided to rely on these vignettes because they resembled the stimuli used in previous studies on efficiency expectations in action anticipation (e.g., Bíró, 2013; Csibra, Gergely, Bíró, Koos, & Brockbank, 1999; Paulus, Hunnius, van Wijngaard, et al., 2011). In addition, the current paradigm had been successfully used with preschool children (Schuwerk & Paulus, 2016).

Our vignettes in these studies depicted an agent on a crossroad. From this crossroad, two paths emerged leading to the other side (but see Study 3 for a different setup). One of the paths was clearly shorter and thus more efficient than the other path. We examined 3- to 6-year-old children's tendency to explicitly predict the agent to take the shorter of the two paths. We also assessed theoretical claims that a clear goal target (or a visible goal state) facilitates teleological reasoning (Bíró, 2013; Gergely & Csibra, 2003). In fact, teleological stance theory claims that a clearly defined goal affects rational action. Therefore, we manipulated the presence of a goal object and the saliency of the goal in some of the studies. In this way, we would be able to evaluate the effect of a clear target goal on efficiency consideration (see Fig. 1).

In Study 1a, we investigated the effect of age and goal state on preschool children's efficiency considerations in their explicit action predictions. The teleological stance theory claims an early onset of efficiency considerations during the first year of life (Gergely & Csibra, 2003). If this is true, we would expect that already the youngest children in our study (3-year-olds) would engage in explicit rational action prediction on a high level. Consequently, there should also be little improvements in the course of the preschool periods. However, if explicit rational action prediction emerges in the course of the preschool years—because it might require flexible manipulation of representations—as one would expect from a representational redescription model (Karmiloff-Smith, 1992), we would expect poor performance in our youngest age group and a clear developmental improvement with increasing age. Because this is the first study to investigate explicit rational action prediction, we first examined whether there is a linear developmental trend (age in months) in explicit rational action of preschool children (without including any other factor), which was the core hypothesis of the study. We also hypothesized that there would be a categorical and linear age difference in success among three age groups (3, 4, and 5–6 years). Note that considering the situational constraints and deciding on a rational option (e.g., selecting the most direct route between two paths leading to the same goal) might develop linearly over the preschool years (see Bartsch & Wellman, 1988; Rothenberg, 1969). Even though U-shaped development in success has been observed in some tasks where children could have contradicting representations at the implicit and explicit levels (Karmiloff-Smith & Inhelder, 1974), many hierarchical tasks that require rational action–control (Thibaut & Toussaint, 2010; Weigelt & Schack, 2010), future thinking (Redshaw et al., 2019), and action prediction for an agent (Bartsch & Wellman, 1988; Rothenberg, 1969) demonstrate linear development in success during the preschool years. We hypothesized that a cognitive representation of efficiency emerges later during the preschool years, which might also affect efficient action control but is directly assessable when investigating children's appreciation of others' actions.

Second, if a clear target facilitates children's action prediction, as teleological stance theory assumes, there would be a difference between the trials with a target object and without a goal object. However, if preschool children have difficulty in constructing the hierarchical relation among the action (going to the other side), target goal (with or without target goal), and the situational constraints (short or long) and then act on these representations, one would not expect a difference between these two conditions. In a follow-up study (Study 1b), we examined the effect of efficiency consideration in only 3-year-old children, where the action state was made more salient via emphasizing that the agent aimed at going to the other side as fast as possible.

If children's difficulty in rational action prediction is acting on their representations and controlling their actions based on these representations, children may explicitly reason about efficiency of the

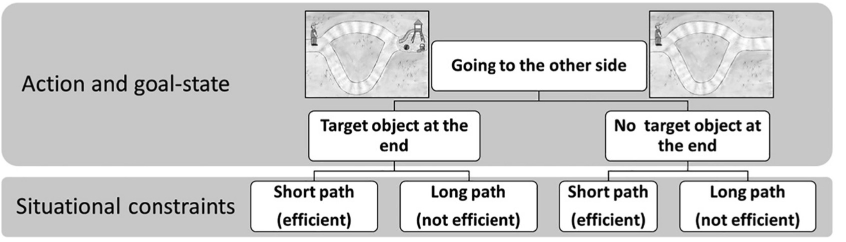

Fig. 1. Hierarchical representation of the overall study design.

action once the action is executed by the protagonist. In other words, if the protagonist selects which path to pursue, children may reason on the protagonist's action selection based on efficiency. Thus, in Study 2, we investigated the effect of age, path (efficient or nonefficient), and target object on children's explicit reasoning on efficiency. Beyond the linear age effect in verbal efficiency reasoning, we hypothesized that children can consider the situational constraints and the target goal about the past events. Note that it has been shown that preschool children's temporal and causal reasoning performance is better on past events compared with future events (McCormack & Hanley, 2011) and that there is a clear linear age trend in performance during the preschool years (McColgan & McCormack, 2008; McCormack & Hoerl, 2007).

In Study 3, we investigated children's efficiency consideration in action prediction and their reasoning about their own action selection by assessing both action prediction and reasoning about actions within the same task. Thus, we were able to explore whether children first come to reason about an action's efficiency before engaging in rational action prediction or whether there is an ability to predict an action based on its efficiency before children start to reason verbally about it, which requires reaching Level E2/E3 in the representational redescription model. In Study 4, we aimed at providing an integrative analysis of our findings regarding action prediction.

Study 1a

Method

Participants and sample size rationale

The final sample included 62 children. To have an even distribution of age groups, the sample consisted of 22 3-year-olds (M = 44 months, SD = 2.1, range = 40–47; 8 boys), 21 4-year-olds (M = 54 months, SD = 3.9, range = 48–60; 13 boys), and 19 5- and 6-year-olds (M = 70 months, SD = 5.8, range = 61–81; 9 boys). One additional child was excluded because she refused to continue the experiment. All participants were typically developing children from a large European city and its surrounding area. They were of mixed socioeconomic status. Informed consent for participation was given by the children's caregivers. Sample size for each age group was equivalent to that in previous studies (e.g., Gredebäck & Melinder, 2010; Schuwerk & Paulus, 2016). For the main test (relation between age in months and rational action prediction), a power calculation for a simple linear regression based on G*Power (Faul, Erdfelder, Lang, & Buchner, 2007) for an effect size f^2 = .15, β = .80 and α = .05 revealed a minimum of 55 participants.

Materials and procedure

The materials consisted of drawings of protagonists at the junction of two paths (see Fig. 2 for examples). Both paths led to the other side, where they converged into one single path again. Importantly, one of the paths was longer than the other because it was U-shaped. A total of 10 drawings with different protagonists (mostly different humans and animals) were created to avoid monotony and to not restrict our exploration to one type of agent only. Half of them had a goal target at the other side, and half of them did not. Path location (short/long path on the upper/lower component) was counter-

Fig. 2. Examples of the test stimuli in Study 1a and Study 1b. The left picture shows a stimulus without a goal object. The middle and right pictures show two stimuli with goal objects.

balanced. That is, for half of the drawings the upper path was the shorter one, whereas for the other half the lower path was the shorter one. Materials further consisted of one additional drawing in which no protagonist was presented (training item).

Children were tested individually in a quiet room. Study sessions were scored online by the experimenter and videotaped for later coding. At the beginning of the session, children were presented with the training item for practice. In the practice trial, the experimenter explained that children would face a plain and that the protagonist could cross the plain by taking one of the two paths (“That’s a surface! You can only walk across the surface on a path!”). Subsequently, the experimenter pointed to the short path noting “Look, this is a short path” and to the long path noting “Look, this is a long path” (the order of presentation was counterbalanced between children). Then, as the first control question, children were asked, “Show me where you can walk here.” The item was presented, and the question was repeated until children correctly showed only paths and not the other parts in the plain. As the second control question, children were asked to point to the short path (“Show me the short path!”) and the long path (“Show me the long path!”). If they hesitated or erred, this part was repeated. All children pointed out the short and long paths correctly. Then, the main task was administered. Children were presented with 10 trials (consisting of the 10 drawings) in a pseudorandomized order. In each trial, the experimenter first introduced the protagonist (e.g., “This is the farmer”; “This is the giraffe”). Then, in trials where there was no goal target on the other side, the experimenter told children that the protagonist wanted to go to the other side while pointing to the other side: “The [protagonist] wants to go to the other side.” In trials where there was a target (target object), the experimenter again first introduced the protagonist and then the target (e.g., “This is a house”; “This is a tree”). After that, children were told that the protagonist wanted to get to this target (e.g., “The farmer wants to get to the house”; “The giraffe wants to get to the tree”). After the instruction, they were asked by the experimenter, “Which path is the [protagonist] going to take?” Note that the respective drawing was present throughout the whole trial (i.e., when introducing the protagonist and when asking children about the paths) so that all information was visually available. The experimenter registered children’s answers, accepting either their pointing to one of the two paths or verbal answers.

Coding and data analysis

We coded the percentage of trials in which children predicted the protagonist would take the shorter path as the dependent variable. Based on our central hypothesis, the main analysis (Model 1) was computed to check the linear relation between the predictor age in months and the outcome variable percentage of short path choices. In addition, to examine more specific differences among age groups and trial types, we constructed another model with the between-participant variable age group (3, 4, or 5–6 years) and the within-participant variable goal object (with or without goal object) (Model 2). We also examined whether children’s predictions were different from chance level (50%).

Even though our results were very robust over different statistical approaches, we selected our models based on whether the assumptions for the linear models were violated and applied robust methods accordingly, especially to prevent Type II error, in all the following studies in this article, including nonparametric tests, generalized linear models (GLMs), generalized estimating equations

(GEEs), and generalized linear mixed models (GLMMs). We also provide the details of the sample statistics and assumption checks to inform future studies on the distributional properties of the explicit rational action prediction and reasoning during preschool years. See the online Supplementary Material 1 for the tested assumptions of the linear models. The data were analyzed with the statistical package SPSS 25 (IBM Corp., Armonk, NY, USA) unless otherwise indicated. Raincloud plots were constructed with an open-source R code (Allen, Poggiali, Whitaker, Marshall, & Kievit, 2019). All the data, analyses syntax from SPSS, and R codes of this study and the subsequent studies can be found at the following Open Science Framework link: https://osf.io/ej43p/?view_only=9da0e15f29c5494885d97087b1cea25ehttps://doi.org/10.17605/OSF.IO/EJ43P.

Results

A preliminary analysis showed no main effect of gender, so this factor was dropped from the further analyses. Model 1, the simple linear regression, revealed a significant effect of age in months on the overall percentage of short path choices, R^2 = .40, $F(1, 60)$ = 39.79, $p \leq .0001$, and the relation was positive (b_1 = 0.01, SE = 0.01, β = .63, $p \leq .0001$) (see Fig. 3). Children predicted the shorter path more often with increasing age.

Model 2, a full factorial GLMM with Gaussian distribution and identity link function and with the between-participant factor age group and the within-participant factor target object (with or without target object) yielded only a significant effect of age group, $F(2, 177)$ = 28.882, $p \leq .0001$. Importantly, there was neither a main effect nor an interaction effect for the factor target object (all other ps > .4689). See Fig. 4 for the descriptive statistics and data distribution. Sequential Bonferroni-corrected pairwise comparisons based on estimated means revealed that the performance of 3-year-olds differed significantly from that of 4-year-olds and 5- and 6-year-olds (p = .0008 and $p \leq .0001$, respectively). The difference between 4-year-olds and 5- and 6-year-olds was also significant (p = .0169). A one-sample Wilcoxon signed-rank test against chance performance (median 50%) showed that the 4-year-olds' and 5- and 6-year-olds' overall performance (averaged across trial types) differed from chance (T = 126.5, p = .0022, and T = 188.5, p = .0001, respectively). Importantly, this was not the case for 3-year-olds (T = 59, p = .3372).

Discussion

Study 1a examined the development of explicit rational action prediction during the preschool period. The main regression analysis indicated a linear developmental trend in rational action prediction from 3 to 6 years of age. Further analyses yielded a strong developmental effect, with 3-year-olds not showing a systematic prediction of the shorter path. In contrast, 4-year-olds and 5- and 6-year-olds expected the protagonist to choose the shorter path. Moreover, across ages, our results revealed no significant differences between vignettes with and without a distinct target object. In contrast to claims by teleological stance theory (Gergely & Csibra, 2003), our data show that rational action prediction is not facilitated by the presence of a clear goal object. This suggests that if the agent's goal (i.e., to get to the other side) was clear enough, no specific target was necessary.

Before discussing our findings in greater detail, we wanted to examine whether one of the causes for 3-year-olds' failure to predict rational action could be a lack of understanding that the protagonist wanted to get to the other side as fast as possible. Even though this has been claimed to be the central assumption underlying the rational action argument (Gergely & Csibra, 2003), and even though it has been argued that infants use efficiency considerations proactively (e.g., Bíró, 2013), one could assume that explicit teleological understanding is facilitated by information that the observed agent indeed has the motivation to act efficiently. To evaluate this possibility, in Study 1b another group of 3-year-olds was examined in the same design, whereas the additional information that the protagonist wanted to get to the other side/its goal as fast as possible was provided.

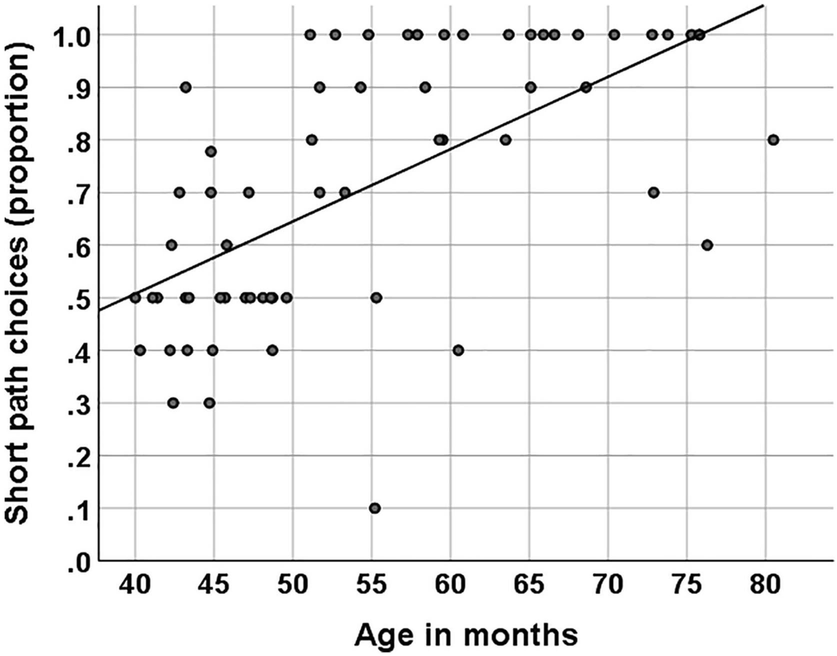

Fig. 3. The relation between age in months and percentage of short path choices in Study 1a.

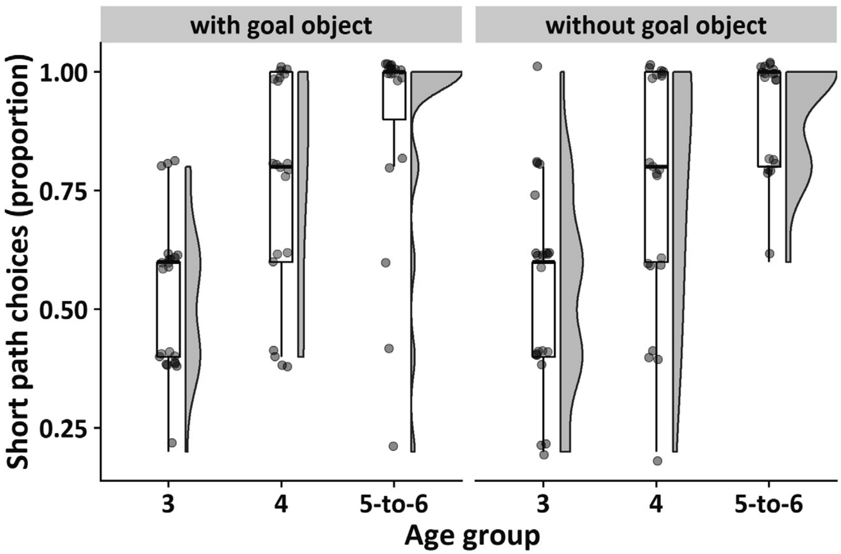

Fig. 4. Raincloud plots for the mean proportion of short path choices in each age group and in the two goal conditions of Study 1a.

Study 1b

Method

Participants

The final sample included another 26 3-year-old children (M = 43 months, SD = 1.9, range = 38–47; 12 boys). An additional 3 children were excluded due to experimenter error or refusal to continue the study. Sample size for this age group was equivalent to that in Study 1a. Participants came from the same region as in Study 1a. Background and informed consent were the same as in Study 1a.

Materials, procedures, and data analyses

The materials were the same as in Study 1a. The procedures were the same as in Study 1a with the following difference: When the experimenter introduced the protagonist's goal (e.g., to get to the house on the other side), it was emphasized that the protagonist wanted to get there as fast as possible ("The [protagonist] wants to go to the other side as fast as possible"). We checked the effect of target goal and also whether children's performance was different from chance (50%).

Results

Paired-sample t-test results revealed that children's tendency to predict the short path choice did not differ between trials with a target object and trials without a target object, $t(25) = 0.263$, $p = .7944$, so data were averaged across trial types. In line with Study 1a, there was no gender difference, so it was dropped from further analyses. One-sample Wilcoxon signed-rank test against chance performance (median 50%) showed that children's behavior did not differ from chance ($T = 87$, $p = .3158$). Moreover, Mann–Whitney U test results showed that there was no significant difference between 3-year-olds' behavior in Study 1a and that in Study 1b ($n = 48$, $U = 305$, $p = .6835$).

Discussion

Study 1b showed that even with the additional velocity information that the protagonists wanted to act as fast as possible, 3-year-olds showed no increased tendency to predict rational action prediction. This result rules out the possibility that 3-year-olds' failure in considering efficiency in action prediction in Study 1a was due to a lack of knowledge on another's inclination to act quickly. Together, Study 1a and Study 1b indicate that explicit rational action prediction follows protracted development across the preschool period. These results might be in line with the representational redescription model, which proposes protracted development of children's ability to consider the efficiency of others' actions explicitly.

However, one might argue that although young children cannot explicitly predict others' actions based on efficiency, they might be able to reason about the actor's action explicitly once it has been executed by the protagonist. Previous studies have demonstrated that 4- and 5-year-olds' temporal and causal reasoning on past events is better than that on future events (McColgan & McCormack, 2008; McCormack & Hanley, 2011; McCormack & Hoerl, 2007). Is it the same for children's verbal reasoning on the efficiency of past events? That is, explicit rational action ability might be more evidenced if children reason post hoc about others' behavior than is the case in a prospective prediction task. Nevertheless, it should also be noted that retrospective reasoning on the actor's action efficiency may be even more demanding compared with prospective prediction in younger age groups. Thus, in Study 2 we explored whether preschool children would reason about the selection of a short path in terms of efficiency (i.e., length or velocity) retrospectively. If we were to find that young preschool children do so, it would suggest that explicit reasoning about others' efficiency develops early in life.

Study 2

In Study 2, the protagonist selected either the short or long way. Afterward, the experimenter asked children why the protagonist chose that way.

Method

Participants

The final sample included 60 children. To have an even distribution of age groups, the final sample consisted of 20 3-year-olds (*M* = 43 months, *SD* = 3.4, range = 36–47; 10 boys), 20 4-year-olds (*M* = 54 months, *SD* = 4.0, range = 48–59; 11 boys), and 20 5- and 6-year-olds (*M* = 70 months, *SD* = 5.4, range = 61–79; 13 boys). An additional 10 children were not included due to refusal to continue the study (*n* = 2), problem in language understanding or comprehension (*n* = 4), or inability to understand the experimental instructions (*n* = 4). The rationale for the sample size was the same as in Study 1a.

Materials and procedure

The materials were the same as in Study 1a. The procedures were the same as in Study 1a with the following difference: After the instruction, rather than asking children about the path, the protagonist took either the short or long path to the other side (in a pseudorandomized order). The experimenter clearly and slowly moved the protagonist along with one of the paths. Afterward, children were asked by the experimenter, "Why did the [protagonist] take this path?" The protagonist selected the short way in half of the trials and the long way in half of the trials. Moreover, a clear object was present in half of the trials was absent in half of the trials.

Coding and data analyses

All responses were placed into four categories: (a) length, (b) velocity, (c) target, and (d) other answers. If children's answers included reasoning about the length of the path or the speed of the agent, these verbal responses were coded as length or velocity, respectively. If children only referred to the target object or the goal of the protagonist, the verbal response was coded as target object. All other responses were included in the last category of other answers (e.g., "I don't know," no answer, total irrelevance, preference, normative). Moreover, because the other answers category also included ignorance (e.g., no answer, "I don't know," total irrelevance), we also compared ignorant answers among age groups separately given that they could be an indicator of verbal competence. Responses were binary coded (1 for yes, 0 for no) for each item, and the total number of responses was calculated for each category and age group (see Table S2 in the supplementary material). For more information about the categories, examples, and comparisons of categories, see Supplementary Material 2. The length and velocity categories are of particular interest because they inform us about the efficiency consideration of participants. These were named as *efficiency reasoning*. Typical examples were "because this path is shorter" for length and "wanted to be faster" or "because he can go faster" for velocity. If participants reasoned on the length of the path and/or the velocity of the protagonist, it was coded as 1 (otherwise 0) for each item. Then, the proportion of efficiency reasoning was calculated as the dependent variable. In Model 1, the role of age in months in efficiency reasoning was investigated. Model 2 investigated factors affecting efficiency reasoning and thus included the between-participant variable age group (3, 4, or 5–6 years) and the within-participant variables trial type (with or without goal item) and path (short or long). The proportion of efficiency reasoning was calculated for each within-participant condition.

Results

There was a significant relation between age group and the answer categories, $\chi^2(6)$ = 88.96, $p \leq .0001$, Cramer's V = .39. Follow-up tests with Bonferroni-corrected significance results (p = .0040) based on adjusted residuals demonstrated which residuals were strong enough to significantly contribute to the overall difference (see Table S2). The 3-year-olds mostly based their answers on the references to the target object (target category) or gave other answers. Unlike the 4-year-olds and 5- and 6-year-olds, the 3-year-olds scarcely considered efficiency (length or velocity category) in their answers. Reference to the target object or the goal dramatically decreased in 4-year-olds, and 5- and 6-year-olds rarely gave answers in the other answers category. See Supplementary Material 2 for further results related to all answer categories and their comparisons. Only 3.16% of the total answers were ignorant answers (e.g., no answer, "I don't know," total irrelevance). These ignorant answers were given by 4.5% of 3-year-olds, 2% of 4-year-olds, and 3% of 5- and 6-year-olds. There were no significant differences among age groups in ignorant answers, $\chi^2(2) = 2.07$, $p = .3961$.

Considering efficiency reasoning, Model 1 (GLM with inverse Gaussian distribution and identity link function) indicated that there was a significant effect of the covariate age in months (Wald $\chi^2 = 10.65$, $p = .0011$) on efficiency reasoning. Model 2 (full factorial GLMM with inverse Gaussian distribution and identity link function), with age group (3, 4, or 5–6 years), path (short or long), and trial type (with or without goal object), revealed a significant effect of age group, $F(2, 228) = 16.57$, $p \leq .0001$, and path, $F(1, 228) = 10.98$, $p = .0011$. Moreover, there was a significant interaction between age group and path, $F(1, 228) = 3.06$, $p = .0486$, and between path and goal, $F(1, 228) = 5.26$, $p = .0227$ (all other ps > .1028). To further examine the main effect of age group, sequential Bonferroni-corrected pairwise comparisons based on estimated means were calculated. Results indicated that 3-year-olds used significantly less efficiency reasoning compared with 4-year-olds, $t(228) = -5.07$, $p \leq .0001$, and 5- and 6-year-olds, $t(228) = -4.58$, $p \leq .0001$. The difference between 4-year-olds and 5- and 6-year-olds was not significant ($p = .4336$). Efficiency reasoning was higher when the experimenter selected the short path compared with the long path. However, investigating the interaction effect between path and age group with the follow-up comparisons showed that only 5- and 6-year-olds reasoned more about efficiency in short path choices compared with long path choices, $t(228) = 3.29$, $p = .0012$, but not 3-year-olds and 4-year-olds (minimum $p > .1845$). In addition, efficiency reasoning when the protagonist selected the short way compared with the long way was higher when there was a goal item, $t(228) = 3.79$, $p = .0002$, but not when there was no goal item ($p = .1012$). See Fig. 5 for descriptive results and the data distribution.

Discussion

In line with the findings of Study 1a and Study 1b on explicit action prediction, the results of Study 2 indicated that over the course of the preschool years children increasingly reason about others' actions in terms of efficiency. Most interesting, 3-year-olds mostly did not engage in reasoning about the efficiency of others' actions even though they provided different and rich answers. The pattern of results thus indicates that children do not consider efficiency information when explicitly reasoning on others' actions before 4 years of age. Results showed that children were more likely to engage in efficiency reasoning when the protagonist selected the short path compared with the long path. Moreover, even though children's overall efficiency reasoning increased with age, having a clear target eased only 5- and 6-year-olds' efficiency reasoning.

We also found that both 4-year-olds and 5- and 6-year-olds engaged in efficiency reasoning—that is, referred to the lengths of the paths and velocity—when the protagonist selected the long path. For instance, some of the 4-year-olds and 5- and 6-year-olds gave the following answers when the protagonist selected the long path: "there is a shorter one here," "because the [protagonist] is fast,", and "because it is longer." The latter one is especially interesting in that it is not clear whether the child protests, questions, or just simply indicates the preference of the protagonist. However, the crucial point here is whether preschool children can evaluate efficiency-related aspects in their verbal reasoning at all via mentioning of length and/or velocity. Most important for our theoretical question is the finding that this is apparently not the case for the youngest group. In fact, 3-year-olds' reasoning mostly included reference to the target or simple preference of the protagonist. At the same time, the ignorant answers were not different among age groups, indicating that the age differences are not due to a lack of explanations in younger children.

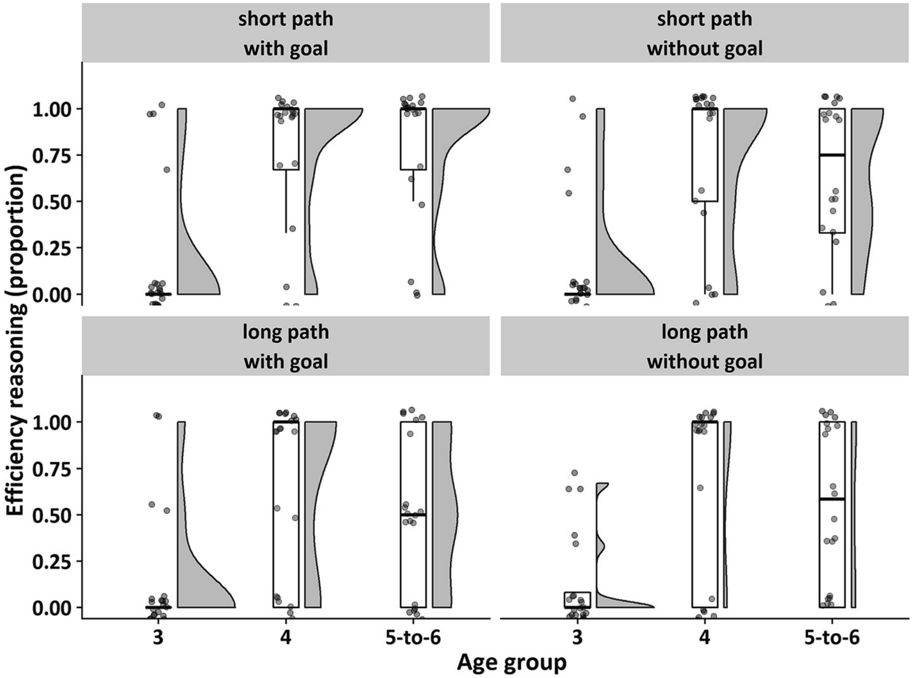

Fig. 5. Raincloud plots for the mean proportions of efficiency reasoning according to age groups, paths, and the goal object in Study 2.

Although the results of Study 1a, Study 1b, and Study 2 converge in the same developmental pattern, it is possible that the length of the path might not have been clear, especially for young children, given that both paths converged into one path. To rule out this concern, we conducted another study.

Study 3

To make the length of the path and to increase the saliency of the goal state, we made some changes in this study. Unlike the previous materials, the two paths did not converge into one path. Instead, the short path and the long path were independent (see Fig. 6). The length of the long path was increased, and there was a goal object at the end of both paths. These three changes made the paths clearly distinct and made the goal more salient. We also combined the experimental paradigms of Study 1a and Study 2. That is, we asked children both which path the protagonist would take and, once children predicted the path selection, why the protagonist would take that path. Hence, it was possible to investigate children's explicit action prediction and their reasoning in the same paradigm. Because we did not have target object manipulation in this study, there were 4 trials instead of 10.

Method

Participants

The final sample included 60 children. To have an even distribution of age groups, the final sample consisted of 20 3-year-olds (*M* = 42 months, *SD* = 3.4, range = 36–47; 10 boys), 20 4-year-olds (*M* = 54 months, *SD* = 3.4, range = 48–59; 7 boys), and 20 5-year-olds (*M* = 65 months, *SD* = 3.3, range = 61–71; 6 boys). An additional 3 children were not included due to inability to understand the experimental instructions. The rationale for the sample size was the same as that for Study 1a. We did not include any 6-year-olds in this study.

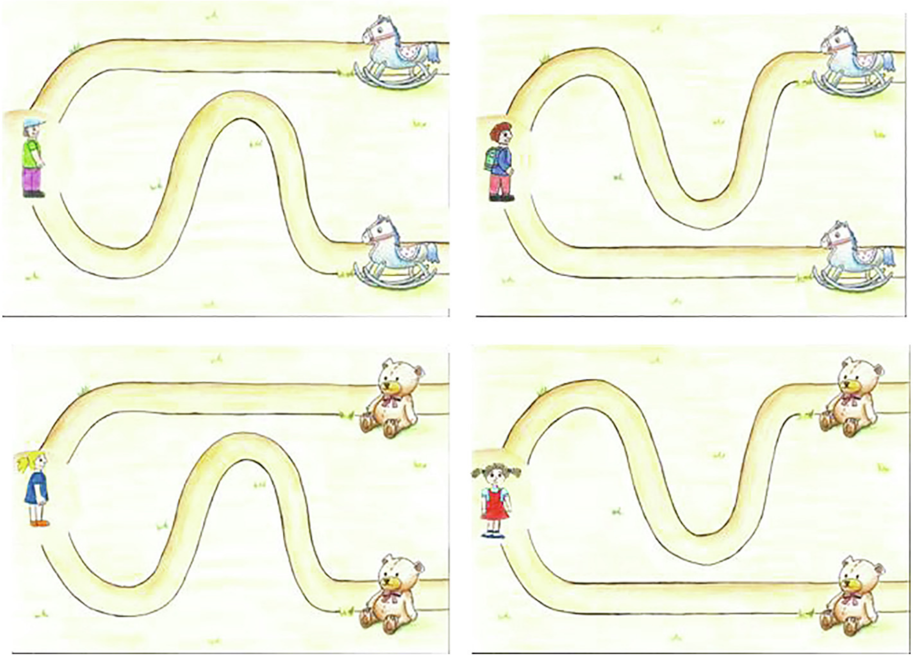

Fig. 6. Examples of the test stimuli in Study 3.

Materials and procedure

Like the previous experiments, the materials consisted of drawings of protagonists at the junction of two paths (see Fig. 6). However, in this study the two paths did not converge into one path but rather were separate. One of the paths was clearly longer than the other path because it was U-shaped. Four drawings with different protagonists were created to avoid monotony and to not restrict our exploration to one type of agent only. All the drawings had two goal targets at the other side. Path location (short/long path on the upper/lower component) was counterbalanced. That is, for two of the drawings the upper path was the shorter one, whereas for the other two drawings the lower path was the shorter one. Materials further consisted of one additional drawing in which no protagonist was presented (training item). The procedure was the same as in Study 1a with the following difference: After the instruction, children were asked by the experimenter both "Which path is the [protagonist] going to take?" and "Why does the [protagonist] take this path?"

Coding and data analyses

Path selection. We coded the percentage of trials in which children predicted the protagonist to take the shorter path as the dependent variable. In Model 1, the role of age in months in the percentages of short path selection was investigated. In Model 2, we examined the effect of age group (3, 4, or 5 years) on path selection performance. To examine whether children's short path selection (averaged across trials) was different from chance, Wilcoxon signed-rank tests against chance (median 50%) were conducted.

Answer categories. Following Study 2, all responses were placed into four categories according to the content of the responses: (a) length, (b) velocity, (c) target object, and (d) other answers ("nonsense," "I don't know," total irrelevance, preferences, or normative). The type of answers (four categories) was compared among age groups (three groups) with a chi-square test and standardized residuals for explorative purposes (see Supplementary Material 2 for comparisons and some examples [Tables S3 and S4]). The length and velocity categories were combined because there were very few examples of velocity. Moreover, following Study 2, answers with ignorance (no answer or "I don't know," "nonsense," or total irrelevance) were also compared among age groups separately.

Efficiency reasoning and its relation to short path choices. Following Study 2, if children's answer included reasoning for velocity and/or length, it was coded as efficiency reasoning in the same way as it was coded in Study 2. Two models (Model 3 and Model 4) were calculated in the same way as described for the short path selection (Model 3 with covariate age in months and Model 4 with the factor age group) with the percentage of *efficiency reasoning* outcome.

Results

Path selection

In Model 1, results of a simple linear regression indicated that age in months was a significant predictor of the percentages of short path selections, $R^2 = .08$, $F(1, 58) = 5.33$, and the relation was positive ($b_1 = 0.007$, $SE = 0.003$, $\beta = .29$, $p = .0245$), indicating that with increasing age children more often chose the shorter path. In Model 2, a GLM (gamma distribution and the log-link function) with the between-participant variable age group (3, 4, or 5 years), results did not yield a significant effect of age group, Wald $\chi^2(2) = 8.23$, $p = .091$, on path selection.[1]

On the other side, Wilcoxon signed-rank test against chance performance showed that 3-year-olds' path selection did not differ from chance ($T = 9$, $p = .7389$), but 4-year-olds' and 5-year-olds' short path selection was significantly above chance ($T = 48$, $p = .0313$, and $T = 93$, $p = .0084$, respectively) (see Note 1). Fig. 7 depicts the descriptive results.

Answer categories

There was a significant relation between age group and answer categories, $\chi^2(4) = 42.97$, $p \leq .0001$, Cramer's $V = .30$. Follow-up tests with Bonferroni-corrected significance results ($p = .0060$) based on adjusted residuals demonstrated which residuals were strong enough to significantly contribute to the overall difference (Table S4). Most important for our research question, these results highlighted that 3-year-olds' answers mostly included references to the target. In contrast, 5-year-olds mostly considered efficiency in their reasoning. In addition, the ignorant answers were 6.3% of the total answers and were significantly different among age groups (Fisher's exact test, $p \leq .0001$). Follow-up comparisons indicated that 3-year-olds gave significantly more ignorant answers than 4-year-olds (Fisher's exact test, $p = .0006$) and 5-year-olds (Fisher's exact test, $p \leq .0001$). Whereas 8.2% of 3-year-olds' total answers were ignorant, only 1.8% and 2.1% of 4-year-olds' and 5-year-olds' total answers were ignorant, respectively.[2]

Efficiency reasoning and its relation to short path choices

In Model 3, with the covariate age in months, GLM (gamma distribution and log-link function), results yielded a significant effect of the covariate age in months, Wald $\chi^2(1) = 15.57$, $p \leq .0001$, on efficiency reasoning. With increasing age in months, children more often engaged in efficiency reasoning. In Model 4, with the between-participant variable age group (3, 4, or 5 years), GLM results demonstrated a significant effect of age group, Wald $\chi^2(2) = 13.00$, $p = .0015$, on efficiency reasoning. Sequential Bonferroni-corrected pairwise comparisons based on estimated means indicated a significant difference between 3-year-olds and 5-year-olds ($p = .0011$) and between 4-year-olds and 5-year-olds ($p = .0144$), but not between 3-year-olds and 4-year-olds. See Fig. 7 for descriptive results.

[1] To examine the effect of each age group and its interaction with the trials separately, a full factorial binary regression (binary distribution with logit-link function) with generalized estimating equations model was used with the between-participant variable age group (3, 4, or 5 years) and the within-participant variable trial (first, second, third, or fourth). A robust estimator was used for the covariance matrix, and kernel log-quasi-likelihood was selected for the model effect statistics. *AR(1)* correlation matrix was selected for the repeated measure. Even though the variable age group was a significant predictor of short path selection, Wald $\chi^2(2) = 8.23$, $p = .0163$, trial and its interaction with age group was not (minimum $p > .7025$).

[2] We also compared ignorant answers of 3-year-olds between Study 2 and Study 3. Results indicated that 3-year-olds gave significantly more ignorant answers in Study 3 compared with Study 2, $\chi^2(1) = 12.81$, $p = .0007$, Cramer's $V = .21$.

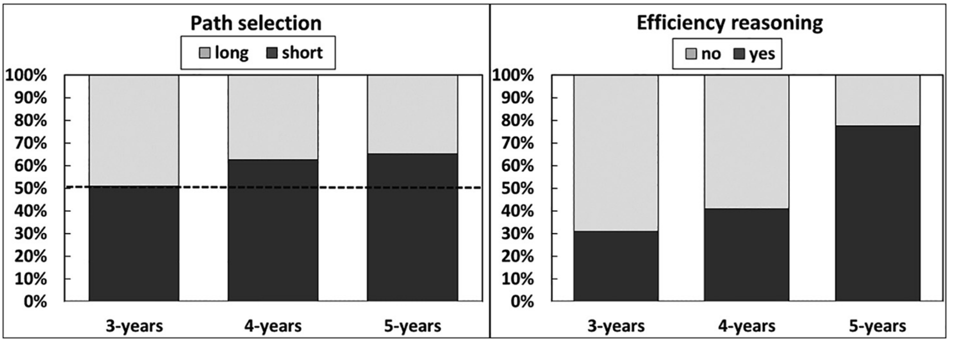

Fig. 7. Percentage of path selections (left) and efficiency reasoning (right) according to age groups in Study 3. The dashed line on the path selection graph represents chance level.

There was an overall significant two-tailed correlation between children's action prediction performance and their efficiency reasoning (r_S = .349, p = .0062). Bonferroni-corrected results (p = .0167) demonstrated that there was a significant relation between the short path choices and children's reasoning about efficiency only in 5-year-olds (r_S = .542, p = .0137) (all other ps > .2571).

Discussion

The results of the current experiment are in line with those of the previous experiments. In the course of the preschool years, children increasingly predict that a protagonist will take a shorter (efficient) path. Moreover, they increasingly rely on efficiency when reasoning about others' actions. This suggests that the ability to explicitly consider others' actions in terms of efficiency develops in the course of the preschool years. Although there is a linear trend, the difference among age groups in their action prediction performance was not significant in a model without the effect of trial. This may stem from decreasing the age range via not including any 6-year-olds in Study 3 and/or using a different set of stimuli with fewer trials. Notably, 4 years of age seems to be a transition period given that 4-year-olds' rational action prediction was significantly different from chance. Yet, it can be inferred from the results that 4-year-olds' verbal efficiency reasoning was more similar to that of 3-year-olds.

In addition, we found that 3-year-olds gave more ignorant answers compared with the other age groups. Comparing ignorant answers between Study 2 and Study 3, we showed that 3-year-olds could provide verbal reasoning when the action is executed by the protagonist. Nevertheless, they have difficulty in explaining their own action selection. This difference might indicate that 3-year-olds have difficulty in explaining their own action selection rather than in understanding the task. This pattern fits to the proposal that in ontogeny humans first learn to understand and reason about others' actions before they direct this ability to their own actions (e.g., Carruthers, 2009; see also Ryle, 1949).

The studies demonstrated that explicit rational action prediction develops in the course of the preschool years and that 4 years might be a transitional age. Before turning to the General Discussion, we aimed at providing an integrative analysis of our findings regarding action prediction. Given that 4 years might represent a crucial age, we also collected more data from 4-year-olds in order to increase the sensitivity of our overall analysis.

Study 4: Integrative analysis

We combined the data from Study 1a, Study 1b, Study 3, and this study (Study 4) in order to highlight developmental changes in children's rational action prediction. Given that Study 2 did not include an action prediction task, it was not included. We also increased the sample size by testing more 4-year-old children for an additional analysis because this age group was the transition age for rational action.

We examined the relation between children's age in months and the percentage of short path choices. Moreover, to find out the exact age-related cutoff (in months) for rational action prediction (above or below chance performance), we applied a receiver operating characteristics (ROC) curve on the data.

Method

Novel participants, procedure, and total participants

There were 148 participants coming from Study 1a, Study 1b, and Study 3. The additional sample included 34 4-year-old children (*M* = 56 months, *SD* = 1.02, range = 55–58; 14 boys). An additional 2 participants were excluded due to an experimenter error. Participants came from the same region as in Study 1a. Informed consent for participation was given by children's caregivers. The materials and procedures were the same as in Study 1a. Finally, we combined the data from Study 1a, Study 1b, Study 3, and Study 4. Overall, the analysis was based on 182 preschool children (M_{age} = 53 months, *SD* = 9.8, range = 36–81).

Coding, data analyses, and sample size rationale

Overall analyses. We coded the percentage of trials in which children predicted that the protagonist would take the shorter path. We examined the effect of age in months on the outcome variable percentage of short path choices. Because some assumptions for the simple linear regression were violated (heteroscedasticity and autocorrelation), the weighted least-squares regression method with 1000 bootstrapped samples was used. Thus, the alpha and standard error values were based on bootstrapped results.

Age in months cutoff. For each participant, it was coded whether the mean performance was below or above chance performance. Namely, if the participant's overall performance in short path choices was at the chance level (50%) or below, it was coded as 0 (*n1*). Above chance performance was coded as 1 (*n2*). We used this coding as the state variable in an ROC curve. Our test variable was age in months. We calculated the cutoff age in months for above chance performance in rational action prediction based on sensitivity and specificity values.

Sample size rationale. A power calculation with the R package *MKpower* (previously *MKmisc*) (Kohl, 2020) for an ROC curve analysis with 95% sensitivity, 5% alpha, 90% power, and 0.10 delta values required at least 170 participants (*n1* + *n2*).

Results

In the overall analysis, the weighted least-squares regression with 1000 bootstrapped samples revealed a significant effect of age in months on the overall percentage of short path choices, R^2 = .18, $F(1, 180)$ = 40.01, $p \leq .0001$, and the relation was positive (b_0 = .031, *SE* = .082, and b_1 = .01, *SE* = .002, *p* = .0011, 95% bias-corrected and accelerated [*BCa*] confidence interval [*CI*] [.009, ,015]). Note that results were very similar when we excluded the additional sample that we added for Study 4, R^2 = .19, $F(1, 146)$ = 34.12, $p \leq .0001$.

For the age in months cutoff, test results for the area under the curve (*AUC*) were fair (*AUC* = .717, *SE* = .038, $p \leq .0001$, 95% *CI* [0.643, 0.790], *n1* = 91, *n2* = 91). From the ROC curve (see Fig. 8), the best age in months cutoff point for the above chance performance in rational action prediction could be identified by the points where the lowest specificity values (*x* axis) and highest sensitivity values (*y* axis) meet. According to the curve, the best cutoff point was 51 months of age. Results were very similar when we excluded the additional sample that we added for Study 4 (*AUC* = .733, *SE* = .41, $p \leq .0001$, *n1* = 78, *n2* = 70, best cutoff point = 50 months of age).

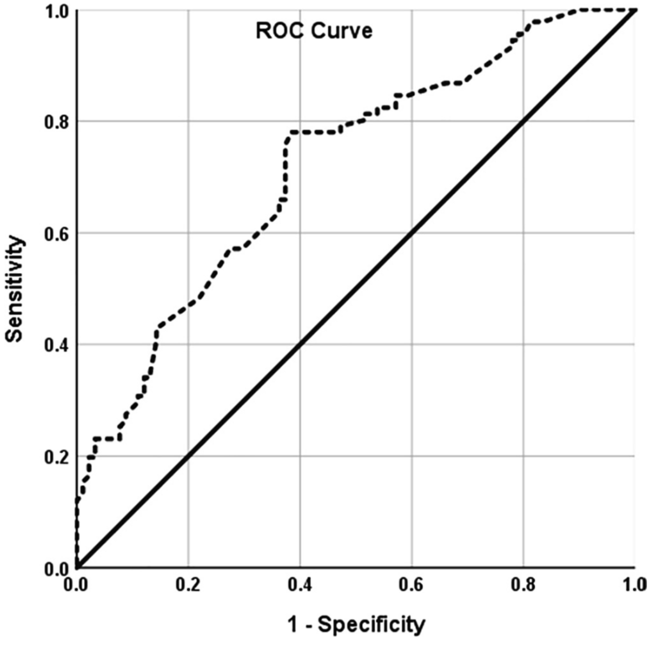

Fig. 8. Receiver operating characteristics (ROC) curve to determine the cutoff age in months range for overall rational action prediction performance above chance level (50%).

Discussion

In this study, our robust regression results with the combined data yielded a developmental improvement on rational action prediction. Finally, results with the ROC curve demonstrated that children's performance on action prediction were mostly above chance level after 50 or 51 months.

General discussion

The current series of studies examined the development of children's ability to take the efficiency of actions into account when predicting others' behavior or reasoning about it. Although efficiency is a key aspect of successful action control (e.g., Bernstein, 1967; Rosenbaum et al., 2012) and affects young children's action execution from early on (e.g., McCarty et al., 1999; Thibaut & Toussaint, 2010; Weigelt & Schack, 2010), children's ability to take this aspect into account when predicting others' actions and when reasoning about others' behavior remained a matter of intense debate (e.g., Juvrud & Gredebäck, 2020; Király & Oláh, 2020; Paulus, 2012). Across three core and two follow-up studies, our results revealed that rational action prediction and reasoning about others' actions in terms of efficiency develops in the course of the preschool years. We expand on the theoretical impact of this finding in the following sections.

The developmental emergence of rational action prediction and the representational redescription framework

Our results provide converging evidence that explicit rational action prediction and reasoning emerges during the preschool years. Overall, our findings relate well to the representational redescription model. Whereas the ability for simple efficient action selection for the agents' own purposes emerges during the first years of life (e.g., Jovanovic & Schwarzer, 2011; McCarty et al., 1999), our results demonstrate that explicitly reasoning about and predicting the efficiency of others' actions is a later developmental outcome that emerges in the course of the preschool period. This is in line with the hypotheses derived from the representation redescription model (Karmiloff-Smith, 1992; see also Cheung & Wong, 2011), which proposes that children first acquire procedural knowledge in a given domain (Level I) and then, in a subsequent step, this procedural knowledge is conceptually re-represented in manipulable forms (Level E1) and then becomes available for theory building and verbal reasoning in the following stages (Levels E2 and E3).

Our overall analyses suggested that children's explicit rational action prediction emerges by 4 years of age. More specifically, further comparisons among age groups revealed that 3-year-olds did not perform above chance level, whereas around 50 or 51 months of age is a sensitive period for the emergence of rational action prediction. Interestingly, whereas 4-year-olds' action prediction was comparable to that of 5- and 6-year-olds given that both age groups predicted above chance that the agent would take the short path, 4-year-olds' reasoning performance was comparable to that of 3-year-olds. This suggests that 4-year-olds first consider efficiency on a more concrete level that is closer to behavior (i.e. concretely predicting the next action step) before reasoning about it in terms of reasons for actions. This finding could be explained by considering Karmiloff-Smith (1992) claim that conceptual redescriptions form an important developmental process during the preschool years. That is, knowledge is first acquired behaviorally in a given domain. By means of a domain-general redescription process, this knowledge becomes generalized and more manipulable (Level E1), which probably develops after 3 years of age in rational action prediction. Nevertheless, one could argue that 3-year-olds and 4-year-olds had difficulty in the task because they (a) did not understand the procedure, (b) were more distracted, (c) had problems with the paradigm employed in the studies, and/or (d) had problems in judging the distance between the short and long paths in general.

First, we employed control questions to ensure that children understood the task. Beyond that, there was no time limit over the trials, and the respective drawing was present throughout the whole trial. These procedures made the instructions clearer and the task more comprehensible. Moreover, related work indicates that 3-year-olds and 4-year-olds can grasp instructions from comparable tasks (see Bartsch & Wellman, 1988; Fabricius & Wellman, 1993; Rothenberg, 1969). That is, the available evidence suggests that our younger participants understood the task. In fact, results of Study 2 showed that even the youngest group understood the instructions and requirements of the task but mostly referred to the goal or the protagonist's preference in their reasoning (see Supplementary Material 2 for example sentences).

Second, if 3-year-olds and 4-year-olds were more distracted, we would have expected to see an overall change in performance over the trials. Yet, results of Study 3 indicated that children's predictions of path choices were robust and above chance performance over the trials, indicating no evidence of distraction, and 3-year-olds were at chance level and there was no effect of trials on their performance. Even though 3-year-olds could understand the length difference between paths, they had difficulty in selecting the efficient path for the protagonist.

Third, one could argue that children had problems with the two-path paradigm employed in the current studies. Considering the main claim of the rational action paradigm (a very early emerging ability to consider the most efficient action via reasoning on the environmental constraints), this ability should be evident in different tasks and setups (Juvrud & Gredebäck, 2020). There are indeed different paradigms that have been used by infancy researchers such as (a) bouncing balls flying around rectangular shapes (e.g., Csibra et al., 1999), (b) an agent reaching for an object (Gredebäck & Melinder, 2010; Skerry et al., 2013), and (c) animated agents walking on two paths (Paulus, Hunnius, van Wijngaard, et al., 2011). We relied on the adaptation of the third infant paradigm that has also been employed with preschool children, and that was validated with adults (Schuwerk & Paulus, 2016) and did not include unusual actions. Notably, this is not the case for all other paradigms, and thus their validity is a matter of concern. For example, Paulus, Hunnius, van Wijngaard, et al. (2011) argued that the results of the flying balls paradigm (see Csibra et al., 1999) can be more easily and parsimoniously explained by infants' appreciation that objects follow surfaces. Thus, instead of being optimal for studying rational action anticipation, this paradigm might assess something different during infancy. At this stage, it is unclear whether if a task based on that paradigm would have been given to preschool children, they would have construed it in terms of efficient behavior. Yet, it should also be noted that there is an ongoing debate on whether what is measured during infancy and later in development with the same task may tap into different underlying factors (Kagan, 2008; Paulus, 2012). Turning back to our paradigm, however, we stress that verbal inquiries demonstrated that children understood the procedure. In Study 2 and Study 3, 3-year-olds gave verbal indications related to the task, but their reasoning rarely included efficiency considerations. Consequently, our evidence does not suggest that young children have problems with the paradigm but rather suggests that they do not consider efficiency in their reasoning.

Lastly, regarding children's ability to evaluate lengths and distances, ample empirical evidence suggests that by 3 years of age children are able to do so. More precisely, it has been shown that at least by 3 years children understand the difference between *short* and *long lengths* (Bartsch & Wellman, 1988; Rothenberg, 1969), understand the complementary relation between *length* and *distance* (Miller & Baillargeon, 1990), process *distance* and *size* information in their representations (Fabricius & Wellman, 1993; Long, Moher, Carey, & Konkle, 2019), infer *distance* information from simple maps and make *spatial scaling* accordingly (Huttenlocher, Newcombe, & Vasilyeva, 1999), and understand concepts such as *near* and *far* (Miller & Baillargeon, 1990).

Even though children can partially evaluate size, distance, and length information as the literature above suggests, our results demonstrate that young children have difficulty in considering the distance information as a situational constraint. In other words, when they are asked to predict a path for a protagonist, which is clearly different from asking the length difference between two paths, younger preschoolers do not take efficiency into account. Thus, it could be asserted that young children have precocious capacity in understanding the parts of the task—such as the aim of the protagonist, the length of the paths, and the goal—and the task as a whole. Nevertheless, their difficulty might be in making the part–whole hierarchical relation when they are asked to select one of the paths to reach the goal for the protagonist. It could be argued that 3-year-olds are still bounded with sequential constraints in rational action prediction. Although they can follow the sequential pattern of action selection (actor → path → goal), efficiency consideration requires acting on this procedural knowledge and considering the length/velocity information regarding the two paths in their representation and re-representing the hierarchical relation to consider efficiency so that they can select the short path. The transition from the procedural Level I representations to Level E1 representation in rational action prediction thus probably occurs around 4 years of age. This point leads us to a related question as to *why* explicit rational action prediction develops around 4 years of age.

The other prominent finding concerns the fact that children's consideration of efficiency in action prediction emerges around 4 years of age, and children are subject to verbal reasoning matching with the efficiency consideration around 5 years of age. Given theoretical assumptions that children's own behavioral competencies inform their action understanding (Harris, 1989; Sommerville & Woodward, 2005), it is possible that children's rational action understanding is supported by their own rational action control, in other words, via taking control over their representations. Children might reach the behavioral mastery in selecting efficient actions for simple tasks earlier such as the one-step tool-use task. Nevertheless, studies on multistep action planning tasks such as end-state comfort effect, future thinking, and hierarchical goal-directed problem solving have shown that children's own rational action selection improves between 3 and 6 years of age (e.g., Gönül, Takmaz, Hohenberger, & Corballis, 2018; Knudsen, Henning, Wunsch, Weigelt, & Aschersleben, 2012; Redshaw et al., 2019; Thibaut & Toussaint, 2010; Weigelt & Schack, 2010). On the other hand, it is possible that young children develop an understanding that others act efficiently by means of repeated experiences with others and their efficient actions (see Green, Li, Lockman, & Gredebäck, 2016; Ruffman, Taumoepeau, & Perkins, 2012). A variety of different factors could be fed into a representational redescription and thus might become available for intra-domain representations such as verbal reasoning and justifications in 5-year-old children, which is Level E2/E3 in the representational redescription model. In other words, both frequency of information (e.g., observing people's efficient actions) and cognitive changes (e.g., the capacity to flexibly modify representations and going beyond sequential constraints) might be at work in tandem in the process of representational redescription.

A final finding was that having a clear goal object did not facilitate children's rational action prediction. Having a target goal facilitated only 5- and 6-year-olds' post hoc reasoning, and only when the protagonist selected the short path. This finding is in contrast to one of the claims by Gergely and

Csibra (2003) on the visibility of the goal state or the saliency of the goal object. In addition, the results were the same even in situations where the protagonist's aim was made salient by the experimenter via emphasizing that the protagonist's goal was to go as fast as possible. Thus, the results bear on the debate on the functions of goals for efficiency reasoning. Notably, one should add that the term "goal" is in itself a rather heterogeneous and unclear concept in that it might refer to a number of different aspects. It has been argued that goal understanding is not a unitary term, and goals might also have hierarchical relations among them (Gozli & Dolcini, 2018). Likewise, action understanding is rather an umbrella term that describes conceptually different processes (Uithol & Paulus, 2014). Others have argued that there are no actions that are not goal directed (Hommel & Wiers, 2017). This vagueness makes it difficult for empirical research to test theories, and we expected progress from further conceptual clarifications and specifications of theories on action understanding.

Implicit and explicit measures of rational action and efficiency consideration

Our theoretical perspective adds to an interpretation of the developmental difference between the results of the implicit tasks (e.g., Bíró, 2013; Csibra et al., 1999; Gergely et al., 1995) and those of the current explicit task. There might be two possible interpretations on how to reconcile the findings on rational action understanding in implicit measures.

On the one hand, if we accept the implicit tasks as evidence for the presence of full-blown teleological reasoning during infancy, our results provide evidence of a gap in preschool children's efficiency consideration between implicit and explicit measures. According to teleological stance theory, an implicit understanding develops already during the first year of life (e.g., Csibra, 2008; Scott & Baillargeon, 2013; Skerry et al., 2013). Yet, there seems to be a delayed manifestation of this competence in an explicit task and when considering verbal reasoning. Importantly, this would suggest that the same developmental pattern revealed in the research on ToM development (cf. Frith & Frith, 2012; Sodian, 2011) is also to be found in another area of social cognitive development, that is, teleological reasoning about others' behavior. If this is true, it would be important to examine in greater detail whether the very same competency subserves both task performances. Considering different task demands between implicit and explicit tasks, explicit prediction and reasoning might be expressed only later in development. Likewise, it is possible that the two-systems account (e.g., Apperly & Butterfill, 2009) also holds for the development of teleological reasoning. Yet, given the current debate on the replicability of (early) implicit ToM findings in infants (e.g., Burnside, Ruel, Azar, & Poulin-Dubois, 2018; Kulke, von Duhn, Schneider, & Rakoczy, 2018), one must await the progress in this area of research.

On the other hand, considering the concerns about the interpretations of the implicit measures (Kagan, 2008; Müller & Giesbrecht, 2008) and skepticism about the hitherto presented evidence for early teleological reasoning (e.g., Beisert et al., 2012; Juvrud & Gredebäck, 2020; Paulus, Hunnius, van Wijngaard, et al., 2011; Paulus, Hunnius, Vissers, & Bekkering, 2011), the current results would point to the very ontogenetic origins of teleological reasoning. Under these premises, our findings would suggest that by around 4 years of age children start to systematically consider the efficiency of others' actions when predicting their future behavior. Yet, it should be noted that we neither directly compared infants with preschool children nor directly compared them with age group implicit and explicit measures. Therefore, we leave it to future research to address this issue.

Limitations, future directions, and conclusion

Although the current studies provide systematic evidence that rational action prediction and efficiency reasoning develop during the preschool years, there are some limitations and open questions for future research. These limitations can be described as possible task and culture relatedness of our results and the need for explaining how rational action is related to other developing abilities such as language and as indirect limitations related to the explanatory power of the representational redescription model and the current state of the theoretical literature.

First, in comparing Study 1a with Study 3, one can see that 4-year-olds' rational action predictions were easily affected by the task characteristics. When there were two goals at the end of the separated paths, 4-year-olds' performance in rational action prediction dropped despite the fact that the long path was clearly longer in Study 3. Because 4 years is a transitional age for rational action prediction, this age group was the most affected group from the stimulus characteristics. It may have been the case that having the goal object at the end of both paths affected 4-year-olds' efficiency consideration in a negative way and made their results close to those of 3-year-olds. In other words, saliency of the target object might have decreased efficiency consideration, potentially due to the hierarchy of goals (Gozli & Dolcini, 2018), or having goals at the end of two separate paths might have obstructed children's hierarchical goal representation. Future studies may also decrease the task demands for younger children, for instance, by making the long path much longer than the short path. In a similar vein, in future research it will be interesting to explore whether the results would be different if different types of materials were to be used (e.g., three-dimensional stimuli). Yet, one should note that previous research has suggested that 3-year-old children have precocious capacity to understand spatial relations inherent in two-dimensional representations such as maps (Huttenlocher et al., 1999). Beyond that, our study was based on one particular paradigm. While this paradigm shares crucial features with other infant tasks (e.g., displays of animated agents; Csibra et al., 1999), and it has been employed with infants (Paulus, Hunnius, van Wijngaard, et al., 2011), older preschool children and adults (Schuwerk & Paulus, 2016), it would be informative to assess preschoolers' ability in different paradigms (Juvrud & Gredebäck, 2020). We leave it to future work to examine preschoolers' developing understanding of efficiency in greater detail.

Second, it should be noted that all children shared a similar cultural background. Considering critical discussions in humanities on the concept and history of *efficiency,* especially among Western cultures (for reviews, see Alexander, 2009; Cobley, 2009), and findings regarding the cultural differences in sociocognitive development (e.g., Redshaw et al., 2019), it would be important to investigate rational action prediction in different cultures.

Third, we considered rational action prediction as an interesting case of application while appreciating the domain-general nature of representational redescriptions in all domains. As Karmiloff-Smith (1992) suggested, the representational redescription model "invokes *recurrent phase changes* at different times across different microdomains and repeatedly within each domain" (p. 6) and "in the human, internal representations become objects of cognitive manipulation such that the mind extends well beyond its environment and is capable of creativity" (p. 192). The intriguing question at this point is how rational action prediction is related to other microdomains and macrodomains. It is well known in the literature that 4 years of age is a turning point for other domains as well such as metarepresentational capacities (Perner, 1991), language (Karmiloff-Smith, 1992), multistep action planning (Knudsen et al., 2012), executive function (Zelazo, 2015), complex reasoning (Zelazo & Frye, 1997), and the ability for reflection (Allen & Bickhard, 2018). In our studies, we also showed that rational action prediction develops at 4 years of age, and verbal efficiency reasoning and efficient action predictions are related by 5 years of age (Level E2/E3). Beyond correlational findings between age-related development and the rational action prediction, future studies should investigate whether efficiency consideration and metarepresentational capacities are cognitively related processes so that the ability for flexible mental manipulations occurs in different domains concurrently (for an extended discussion, see also Karmiloff-Smith, 1994).

In the current studies, the predictions of the representational redescription model were rather simplified because we focused only on an increase in performance with increasing age. Specifying the underlying psychological processes would allow for more specific predictions and stronger tests. That is, there is a need to explain how explicit rational action emerges with a more specific and well-grounded theory. In our studies, contrary to the assumptions of the teleological stance theory, none of the goal-, action-, and situation-related manipulations led to changes in 3-year-olds' performance, and our results were mostly in line with the representational redescription model. Thus, we believe that this model can be a good starting point in the process of building a more specific and differentiated theory for rational action prediction.

In conclusion, across three main studies and two follow-up studies, we demonstrated that explicit rational action prediction emerges during the preschool years. The 3-year-olds did not take efficiency into account when making decisions even when there was an explicit goal, the task was simplified and made more salient, and they were questioned after exposure to the agent's action. On the other hand, the 5- and 6-year-olds considered efficiency information in their explicit action predictions and reasoning about others' actions, whereas 4 years was shown to be a transition age for rational action prediction. This suggests that an important aspect of human action understanding emerges during the preschool years around 4 years of age.

Acknowledgments

We are thankful to Marina Kammermeier, Sarah Frankenthal, Sarah Ofner, Monika Wörle, and Stefanie Brock for support with stimuli design, data acquisition, and coding. We also thank Özgün Köksal and Saskia Melzel for their comments on the earlier versions of the manuscript.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jecp.2020.105035.

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