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The development of children's and adults' use of kinematic cues for visual anticipation and verbal prediction of action

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ABSTRACT

Expectations about how others' actions unfold in the future are crucial for our everyday social interactions. The current study examined the development of the use of kinematic cues for action anticipation and prediction in 3-year-olds, 4-year-olds, 10-year-olds, and adults in two experiments. Participants observed a hand repeatedly reaching for either a close or far object. The motor kinematics of the hand varied depending on whether the hand reached for the close or far object. We assessed whether participants would use kinematic cues to visually anticipate (Experiment 1; *N*=98) and verbally predict (Experiment 2; *N*=80) which object the hand was going to grasp. We found that only adults, but not 3- to 10-year-olds, based their visual anticipations on kinematic cues (Experiment 1). This speaks against claims that action anticipations are based on simulating others' motor processes and instead provides evidence that anticipations are based on perceptual mechanisms. Interestingly, 10-year-olds used kinematic cues to correctly verbally predict the target object, and 4-year-olds learned to do so over the trials (Experiment 2). Thus, kinematic cues are

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used earlier in life for explicit action predictions than for visual action anticipations. This adds to a recent debate on whether or not an implicit understanding of others' actions precedes their ability to verbally reason about the same actions.

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Introduction

Understanding others and having an expectation about how their action unfolds in the future is crucial for our everyday social interactions (Sebanz & Knoblich, 2009). It allows for cooperation with others (Bekkering et al., 2009), fluent interactions (Meyer et al., 2016), and successful task completion (Brownell & Carriger, 1990). Thus, investigating its development has become a key question in developmental science (Bartsch & Wellman, 1989; Carpendale & Lewis, 2004; Ganglmayer et al., 2019; Monroy et al., 2018). Whereas a long-standing tradition in cognitive developmental research has focused on how children reason about others' mental states in their action explanation (e.g., Astington & Barriault, 2001; Wellman, 2014), more recent research has started to explore how children process and understand the stream of ongoing actions (e.g., Hunnius & Bekkering, 2014; Uithol & Paulus, 2014). The current study focused on one feature that plays a prominent role in current debates on the development of action understanding: Do children rely on kinematic cues—that is, "the trajectory and the velocity profile of the action" (Kilner, 2011, p. 352)—of others' behavior to understand their actions? This question is particularly interesting because it is central for an influential framework on the development of action understanding. In the following, we first introduce the theoretical frameworks before we expand in detail on the use of kinematic cues for action understanding.

Mechanisms of action understanding: Direct-matching theory and perceptual processes

One influential family of theories, the so-called simulation theories, stresses the notion of internal simulation processes in action understanding. According to simulation theories, we understand and predict others' actions by using our own mind to simulate the mental processes of others (e.g., Gallese et al., 2004; Goldman, 2006; Gordon, 1995; Rizzolatti et al., 2001). This framework comprises several variants (i.e., several theories) that considerably differ from each other. For example, some theories regard simulation as a rather cognitive process of putting oneself into the others' shoes and understanding others' mental states (Goldman, 2006), whereas other theories propose that simulation takes place on the level of the motor system (Jeannerod, 2001).

One theoretical formulation that gained prominence also in developmental science is the direct-matching theory (DMT) of action understanding, according to which we understand others' action goals by matching an observed action onto our own motor repertoire (Gallese et al., 2004; Rizzolatti et al., 2001; Rizzolatti & Sinigaglia, 2010). That is, according to this approach, observing an action elicits a motor activation in the observers' cognitive system that is similar to the one the observers have when performing the action themselves. Mirror neurons are proposed to be either a neural indicator or the neural basis of this matching process. This process is supposed to allow us to "understand directly the goal of the actions of others without needing inferential processing" (Rizzolatti & Sinigaglia, 2010, p. 268). Thus, from a developmental perspective, it has been proposed that with increased motor abilities, children become able to increasingly understand others' goals or even intentions (Woodward, 2009). The current study focused on this approach from the broader family of simulation theories.

Empirically, there is evidence indicating a close relation between action production and action perception in children (Ambrosini et al., 2013; Daum et al., 2011; Kanakogi & Itakura, 2011; Kochukhova & Gredebäck, 2010; Rosander & von Hofsten, 2011). Most direct evidence comes from studies investigating proactive gaze movements. Given that anticipatory fixations are crucial to perform visually guided actions, the presence of similar anticipatory eye movements when observing someone else performing the same action has been taken as evidence for the direct-matching account (Falck-Ytter et al., 2006; Flanagan & Johansson, 2003; Kanakogi & Itakura, 2011). For example, Falck-Ytter et al. (2006) showed that 12-month-olds and adults, but not 6-month-olds, visually anticipate a bucket in which an actor is about to place a toy. They interpreted their findings as support of DMT; only 12-month-olds and adults, but not 6-month-olds, master the observed action themselves, can match the observed action onto their own motor repertoire, and therefore are able to anticipate the target of the action (i.e., the bucket). However, they used a single, highly salient target object (a red bucket with a three-dimensional happy face connected to it) that had been placed in the direction of the placing movement. Thus, it cannot be ruled out that the visual fixations were based on lower-level perceptual mechanisms.

Indeed, another theoretical perspective highlights the role of perceptual processes and statistical learning in processing and anticipating others' actions (e.g., Hunnius & Bekkering, 2014; Ruffman et al., 2012; see also Smith et al., 2018). Thereby, infants make use of a variety of cues when anticipating future events. Moreover, learning about others' behavior is supported by recognizing perceptual regularities. Indeed, spatial relationships (such as physical proximity) seem to play a key role during learning to anticipate repetitive events in the visual domain (Saffran & Kirkham, 2018). Moreover, empirical studies demonstrating that young children anticipate an upcoming action based on how the action was performed previously are taken as evidence for the role of statistical learning (e.g., Paulus et al., 2011; Schuwerk & Paulus, 2016). With respect to the results of Falck-Ytter et al. (2006), 12-month-olds have observed considerably more placing actions than 6-month-olds. By extracting regularities across several observations, one could speculate that they might have learned that a placement movement usually continues in its initial direction and does not make a sudden shift. In other words, the direction of a movement might be a reliable indicator of where the action will go. Thus, the results might also be explained by 12-month-olds, as opposed to 6-month-olds, being able to anticipate the general movement direction until their gaze hits an interesting object located within that direction. Interestingly, a computational model resting on the assumption that the recognition of biological movements is based on learned prototypical patterns could account for movement recognition (Giese & Poggio, 2003). The authors argued that "attention and top-down influences are not necessary" for basic motion recognition (Giese & Poggio, 2003, p. 190). Such learned prototypical motion patterns (which could be seen as bottom-up processes) might also account for anticipatory eye movements. These processes do not come with an understanding of others' goals or intentions (as implicated by DMT) and nonetheless result in—from the observer's point of view—meaningful action anticipations.

Furthermore, gaze shifts can be triggered by non-foveal retinal stimulation (Harris, 1989). Thereby, more centrally presented stimuli are attended before peripheral stimuli (visual eccentricity; Wolfe et al., 1998). That is, the probability that a saccade is triggered by a certain area of a stimulus depends on how peripheral it is and also on the saliency of the stimulus. Empirical evidence for perceptual explanations in the field of action understanding comes from a study showing that adults anticipate the nearest of several objects being placed in the direction of a movement when they have no further information about the target of the action (Rotman et al., 2006). Similarly, infant work shows the impact of mere perceptual features. For example, infants are more likely to fixate on a large goal area than on a smaller goal area (Adam et al., 2016). The authors interpreted this effect as showing a saliency effect. Notably, in some studies the target even comes with additional salience cues such as being particularly bright or showing a light effect. For example, regarding the results of Falck-Ytter et al. (2006), it is possible that the salient bucket supported or even elicited visual fixations in 12-month-olds and adults. Overall, one could wonder to what extent visual eccentricity and/or saliency of an object plays a role and to what extent this role changes across early development. The observation of a movement triggers an observer to shift gaze in the same direction, and it is more likely that this first fixation goes to the first distinct object that is saliently different from the background (e.g., a distinct object in a different color).

In the context of these different perspectives, kinematic cues are particularly interesting. Following the direct-matching hypothesis, children should be able to process others' actions based on the kinematic cues that are typical for their own behavior. Thereby, kinematic cues play a special role in action understanding that is conceptually different from mere perceptual processes. Theoretical frameworks on the role of perceptual processes do not assign a special role to kinematic cues. Rather, they are just one type of perceptual cue among many others. In the next section, we review work on children's use of kinematic cues in their action understanding.

The development of the use of kinematic cues for action understanding

Although an investigation of the use of kinematic cues for action understanding offers unique possibilities to test the DMT, few developmental studies have done so (e.g., Ambrosini et al., 2013; Filippi & Woodward, 2016; Stapel et al., 2015). A closer examination indicates that the results are rather inconclusive, often due to covarying different components and features in the same design. One set of studies focused on congruency between hand shapes and object form. In one study, 13-month-olds watched six identical trials of a grasping movement with either a congruent hand shape or an incongruent hand shape (matching or not matching the orientation of a to-be-grasped rod; Filippi & Woodward, 2016). Infants anticipated the target only when the hand shapes were congruent. Noteworthy, the incongruent shapes did not elicit anticipations to the incorrect target, as would have been expected if infants' anticipations had been based on the kinematic cues such as movement acceleration and trajectory. Moreover, infants anticipated the actual object the hand was going to grasp in both conditions (i.e., irrespective of the kinematic cues) when they grasped the objects themselves before observing the grasping. Thus, the results seem not to allow for a clear conclusion about infants' use of kinematic cues for action anticipation. Notably, given that participants watched exactly the same grasping in all six trials, they might have learned which object the hand was going to grasp. This would rather speak for the role of perceptual processes and slow learning of the relevance of kinematic cues—rather than kinematic cues playing a special role. Similarly, Ambrosini et al. (2013) showed 6-, 8-, and 10-months-olds and adults a hand reaching toward one of two different-sized objects with a whole hand grasp, a precision grasp, or a closed fist. They found that participants anticipated the action faster if the hand was pre-shaped (whole hand or precision grasp) compared with when the actor reached for one of the balls with the closed fist. Yet, not being able to grasp with a closed fist is something else than the processing of kinematic cues. Thus, besides valuable contributions of both studies to our understanding of action anticipation in infancy, neither study found clear evidence for or against infants' use of kinematic cues for action anticipation.

Another set of studies focused on children's processing of movement speed. For example, a study by Stapel and colleagues (2015) explored the impact of velocity information on infants' and adults' visual fixations in a setup where an actor could press one of two buttons. One of the buttons was closer, and the other one was farther away. There was a strong tendency of all age groups to first look at the closer button. This relates well to findings that adults anticipate the nearest object being placed in the direction of a movement (Rotman et al., 2006). In addition, 15-month-olds' fixations, but not those of 9- and 12-month-olds, were affected by the velocity of the movement. However, this study also manipulated the size of the target objects, a factor that has an effect on the likelihood of anticipations (Adam et al., 2016). Thus, it would be valuable to explore the impact of kinematics independent of an additional manipulation of object size. Using electroencephalography, Hilton et al. (2021) reported neural correlates of 12-month-old infants' processing of boundary cues in action sequences (e.g., slowing down one action before starting the next action), but it remains open to what extent this contributes to infants' action understanding.

Empirical evidence that children incorporate kinematic cues to verbally reason about others' actions comes from a study by Bello et al. (2014). They presented 3- to 7-year-olds with pictures of hand–object interactions with varying motor kinematics. By 3 years of age, children were able to discriminate actions such as touching and grasping an object. At the same time, deciding whether an object was grasped to be used versus grasped to be placed somewhere else based on the handgrip turned out to be challenging—even for the older children. Although performance increased with age, only 6- and 7-year-olds reliably used the grip information to interpret the action. This points to a rather late development of the use of kinematic cues when reasoning about the intention of an observed action.

In sum, although the manipulation of motor kinematics seems to allow putting simulation theories such as DMT at test, further research is needed on children's use of kinematic cues for action anticipation and prediction. To date, the evidence is inconclusive. Our study aimed at contributing to the literature and at testing a central claim of DMT by empirically investigating whether kinematic cues play a special role in action understanding. That is, we investigated the development of children's use of kinematic cues to anticipate or predict others' actions while excluding visual inequalities of the target objects (by using two objects of the same size and color) and by reducing the influence of actor–target associations (by presenting the grasping of one of two objects in a pseudo-random order).

To distinguish between direct-matching and perceptual accounts, it seems essential to introduce at least two visually identical targets that are both placed within the general direction of the movement and that would be approached by different motor kinematics. Notably, different actions are characterized by different motor kinematics (Barrett et al., 2008; Gottwald et al., 2017; von Hofsten & Rönnqvist, 1988; Zaal & Thelen, 2005). According to DMT, perceiving the kinematics of an action should allow for a simulation of how the action unfolds and thus for a correct anticipation of prediction of its target. A critical test to distinguish between the DMT and perceptual accounts seems to be to provide observers with kinematic cues that vary as a function of the target location while controlling for other visual differences. If DMT is correct, we would expect that the kinematic cues can be used to anticipate the target. On the other hand, if anticipations are based on general perceptual mechanisms, kinematic cues have no special role (i.e., priority above other perceptual cues) and, given the saliency of the nearer object, we would expect anticipations in the direction of the movement with an anticipation bias toward the closest target (Rotman et al., 2006).

Different aspects of action understanding: Visual anticipations and verbal prediction

Action understanding has been used as an umbrella term and is composed of various behaviors and competencies (Uithol & Paulus, 2014). It comprises both nonverbal aspects and verbal aspects. These different aspects are often referred to as *implicit* and *explicit* understanding (e.g., Low & Perner, 2012). In this article, we define implicit understanding as forms of implicit knowledge that are expressed on the level of action and perception, whereas explicit knowledge is demonstrated by verbal (or other symbolic) responses and/or language-based processing. Only the latter form allows explicating knowledge and reason about events (Brandom, 1994) and thus constitutes a different level of knowing. Usually, these two forms relate to different measures. Most prominently, nonverbal gaze measures such as looking time and visual anticipations (*implicit* measures) and verbal predictions (*explicit* measures) are paradigmatic for the different forms of knowledge. Both types of measurement approaches have been used to examine how children process others' actions.

Anticipation studies have shown that infants in the first year of life start to proactively visually fixate on the target of someone's action—long before they are able to verbally predict others' actions (e.g., Cannon & Woodward, 2012; Falck-Ytter et al., 2006; Hunnius & Bekkering, 2010; Kochukhova & Gredebäck, 2010). This line of research, relying on measures of infants' perception and visual attention, has led to the predominant view that children develop an implicit understanding of others' actions before showing an explicit understanding. This "implicit precedes explicit understanding account" suggests that young children first implicitly understand others' actions before they are able to translate their implicit understanding in explicit terms, that is, into language (e.g., Baillargeon et al., 2010).

However, there is a recent debate about whether this is always the case (Barone et al., 2019; Grosse Wiesmann et al., 2017). Indeed, other studies have shown that children first correctly verbally predict others' actions before correctly anticipating them (Paulus et al., 2017; Schuwerk & Paulus, 2016). For example, Paulus et al. (2017) showed that 2.5-year-olds use verbal information about an actor's goal to predict the action but do not use the information to correctly anticipate the action. Thus, concerning some aspects of human action, children might first need to learn to reason about it before correctly anticipating it.

According to an "explicit proceeds implicit understanding account," more complex forms of understanding are first acquired on a verbal and explicit level. With increasing experience within an area and automatization, this knowledge can then be transformed into an implicit way of understanding.

This is similar to a situation in which one learns to drive a car; after explicit instruction, the knowledge and routines become automatized, that is, part of the implicit action repertoire. This account ties in with proposals that explicit understanding is something other than merely the translation of what is already there on an implicit level in words (Piaget, 1976). Correctly anticipating others' behavior based on rather subtle cues might constitute a skill that capitalizes on rich experiences of reasoning and talking about others' actions (cf. Carpendale & Lewis, 2004).

Overall, these views lead to the additional developmental question of to what extent the implicit or explicit understanding of different aspects of others' actions develops earlier (Barone et al., 2019; Grosse Wiesmann et al., 2017; Paulus et al., 2017). Although there is little doubt that developmentally the prerequisites for explicit understanding (e.g., verbally reasoning about others' behavior) develops later than the prerequisites of implicit understanding (e.g., visually anticipating the course of others' actions), understanding the different aspects of human behavior could go different ways. Our study aimed at contributing to this debate by examining whether children show successful visual action anticipation and verbal action prediction at the same age or whether one precedes the other, adding to discussions about the developmental sequence of implicit and explicit action understanding.

The current study

In the current study, 3-, 4-, and 10-year-olds and adults observed a hand reaching for one of two objects. Both objects were located in the movement direction of the reaching hand, with one closer and one farther away from the initial position of the hand. The motor kinematics of the hand varied depending on whether the hand reached for the close or far object. In two experiments, we assessed whether participants would use the kinematic cues (a) to anticipate and (b) to predict the target the hand was going to grasp.

We aimed at answering two main questions. First, do children base their anticipations on kinematic cues or on other perceptual mechanisms? DMT would predict that children should use kinematic cues early in life to anticipate which of two objects (both being placed within the direction of the grasping movement) an actor is going to grasp. Yet, if lower-level perceptual mechanisms guide children's action anticipations, we expect them not to make use of the specific kinematic cues to anticipate the target. Instead, we expect them to either randomly anticipate one of the two targets or, when assessing visual anticipations, to show a preference for the nearer target (see Rotman et al., 2006). We wanted to see whether kinematic cues really play a special role as assumed by DMT.

The second question was the following: Do children start to use kinematic cues for implicit action anticipation and verbal action prediction at the same age? If the use of kinematic cues is a rather effortful and slow process that develops later in childhood, we would expect children to initially use kinematic cues in verbal predictions. On the other hand, if kinematic cues are used in a rather automatic fashion from early on in life, we would expect children to be able to use them for both action anticipations and action predictions.

We chose 3-year-olds as our youngest age group because at this age children are able to grasp objects and adapt their motor trajectory for grasping (Gottwald et al., 2017, 2019) Thus, motor simulations of the perceived grasping action should be possible. We included 4- and 10-year-olds because further work suggested that by age 4 children develop increased abilities for reflection (Allen & Bickhard, 2018; Allen et al., 2021) and that reasoning about actions based on kinematics further improves across middle childhood (Bello et al., 2014). In addition, we included an adult group because by this age kinematic cues are processed and used for action understanding. This allowed us to map developmental differences in children's emerging appreciation of kinematic cues and to test age differences in using these cues for implicit action anticipation (as assessed by visual anticipations) and explicit verbal action prediction.

Finally, we presented participants with several trials in which an agent grasped for objects. This gave us the opportunity to study learning effects. In case kinematic cues do not play a special role and are not initially guiding action anticipation and prediction, it is possible that participants learn to focus on the cues in the course of several trials.

Experiment 1: Action anticipation

Method

Sample size

Previous research found an effect size of d = 1.31 for 12-month-olds and d = 1.84 for adults between proactive gaze movements during observing a human action compared with a non-human action (Falck-Ytter et al., 2006). Following this research, an a priori power analysis for a mixed analysis of variance (ANOVA) with an alpha of.05, a power of.80, and an effect size of f = .33, four groups and two measurements (close and far) in G*Power 3.1.9.2 (Faul et al., 2009) was calculated and revealed a sample size of 80. Thus, we aimed at assessing at least 80 participants in each of the two experiments (at least 20 per age group).

Participants

The final sample of Experiment 1 included 98 participants. After the minimum of 20 participants was reached, data collection was continued in case there were further interested participants, leading to small variations in the number of participants per age group. The sample comprised 28 3-year-olds (*M*=3;4 [years;months], *SD*=2.25 months, range = 37–47 months; 12 girls), 20 4-year-olds (*M*=4;4, *SD*=3.02 months, range = 48–57 months; 13 girls), 30 10-year-olds (*M*=10;4, *SD*=1.62 months, range = 121–126 months; 15 girls), and 20 adults (*M*=24;5, *SD*=3;6, range = 18–29 years; 11 women). Exact birth dates of 2 3-year-olds and 3 adults were not noted due to experimenter error. Additional 3-year-olds (n = 1), 4-year-olds (n = 4), 10-year-olds (n = 2), and adults (n = 1) were tested but not included due to lack of eye-tracking data. Participants came from a large city in Germany. Children were recruited from birth records. Informed consent for participation was given by children's caregivers and adult participants. Parents received travel cost compensation, and children were given a small gift. Adult participants were recruited from a student population and got course credit or were paid for their participation. Ethics approval was obtained from the local ethics board.

Stimuli

Stimulus material consisted of a video divided into a familiarization phase and a testing phase. Stimuli were validated by asking 10 adults to evaluate how foreseeable it is that the hand reaches for one out the two objects based on the motor kinematics. Answers were given on a 5-point scale where 1 = *not foreseeable at all,* 2 = *rather not foreseeable,* 3 = *I don't know,* 4 = *rather foreseeable,* and 5 = *very clearly foreseeable.* Overall, they evaluated the stimuli as foreseeable (*M*=4.25, *SD*=0.79).

Familiarization. At the beginning of the familiarization phase, a red screen flashed three times while a sound was played to attract participants' attention. Afterward, a still image with a dark background and a wooden block (the obstacle) lying on a table was presented (Fig. 1, left panel). On the right side of the block, a hand laid palm downward on the table directed to the wooden block. On the left side, a small blue cube was placed on a sheet of paper. The area above and to the left of the wooden block was covered by an occluder, that is, a blue rectangle. This image was used to familiarize participants with the general scenery. The presentation of this still image was briefly interrupted twice (first by a sound accompanied by a black screen and then by a sound accompanied by a red screen) to get participants' attention to the screen. As depicted in Fig. 1, the hand then started a grasping movement over the obstacle, disappeared behind the occluder, and reappeared above the blue cube. The hand reached for the blue cube but did not lift it. This video sequence was repeated six times with an attention-getter after the third and sixth trials. With the video, we ensured that participants understood that the hand reached for the cube, that it reached over the obstacle, and that it was hidden when behind the occluder but reappeared to grasp the cube.

Test trials. The scene of the testing video differed in one crucial aspect compared with the familiarization video: instead of a single cube on the left side, there were two blue cubes presented next to each other: one closer to and one farther away from the hand (Fig. 2). The presentation sequence of the still

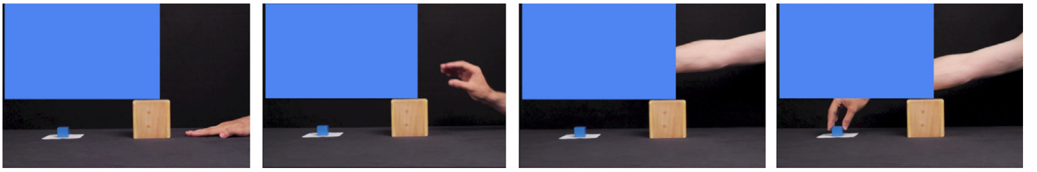

Fig. 1. Snapshots of the familiarization video showing the grasping of the single cube.

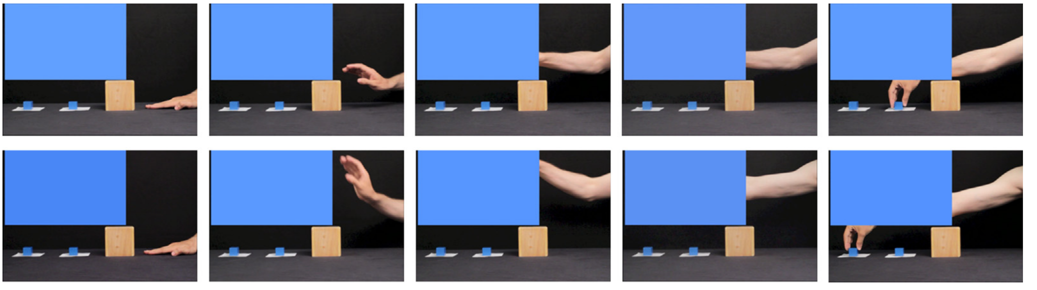

Fig. 2. Snapshots of the videos demonstrating the grasping of the close cube (top row) and the far cube (bottom row) during the test phase.

image, the black and red screens, and the grasping movement was identical to that in the familiarization phase. The motor kinematics, however, differed depending on whether the hand reached for the close cube (Fig. 2, top row) or the far cube (Fig. 2, bottom row) inasmuch as the reaching movement toward the far cube was more pronounced, at greater height, and faster than that toward the close cube. For both the close and far cubes, the hand initiated a reaching movement over the obstacle, disappeared behind the occluder, moved a bit farther, and briefly (1.5 s) stopped there. Finally, the hand started to move again behind the occluder and reappeared above one of the cubes and grasped it without lifting it. Between trials, a black screen (400 ms) was presented. After six trials, an attention-getter was presented to maintain participants' attention.

Apparatus and procedure

Eye movements were recorded with a Tobii T60 eye tracker (60-Hz sampling rate; Tobii Technology, Stockholm, Sweden). Participants sat about 60 cm away from an integrated 17-inch′ TFT monitor (1280 × 1024 pixels) on which the stimuli were presented. They were told that they were going to watch a movie. Data were collected and analyzed with Tobii Studio (Tobii Technology). After participants had watched the six familiarization trials the testing phase started. Each participant was tested on five close (C) and five far (F) cube trials. Participants were randomly assigned to one of two conditions in which the close and far cube grasping movements were presented in a pseudo-random order (CFFCCFFCFC or FCCFFCCFCF).

Measures

The Tobii standard fixation filter with a velocity threshold of 35 pixels/window and a distance threshold of 35 pixels was used to identify fixations. Participants' eye gazes were measured during the time the hand was behind the occluder. The measurement interval lasted 0.84 s (start: hand behind occluder; end: one frame before the hand reappeared) in the familiarization trials and had the same length of 1.93 s for both the close and far testing trials. The measurement interval of the testing trials was chosen to maximize the measurement time for the close trials. Thus, in the close trials the measurement interval started as soon as the hand was behind the occluder and lasted until one frame before the hand reappeared. The movement duration in the far trials was longer than that in the close trials. For experimental comparability, the measurement interval in the far trials (in which the hand was behind the occluder for 2.79 s in total) was thus shortened to fit the length of the close trials. As the hand moved faster in the far condition compared with the close condition, we decided to give participants a bit more time in the beginning to process and anticipate the action. Thus, this led to a measuring interval starting at around 400 ms after the hand stopped behind the occluder and ending around 400 ms before the hand reappeared behind the occluder. Three areas of interest (AOIs) were defined: two goal AOIs around the target objects, each covering 5.26% of the screen (Fig. 3), and another AOI covering the whole screen (100%) to control for gazes directed to the screen but to neither of the two goal AOIs. Similarly, for familiarization trials one AOI covering 5.26% of the screen was defined around the cube, and another AOI covered the whole screen. To be included in the analyses, participants needed to show eye-gaze data (i.e., fixations to the screen) in at least two of the five test trials for each condition. Trials in which participants showed no eye-gaze data were excluded from further analyses (far—3-years-old: 13%; 4-years-old: 10%; 10-year-olds: 5%; adults: 4%; close—3-years-old: 18%; 4-years-old: 9%; 10-year-olds: 5%; adults: 6%).

Three measures were calculated for analyzing participants' gaze behavior: a frequency score, a first fixation score, and a differential looking score (DLS). The former assessed participants' anticipation to the cubes (irrespective of being the correct or incorrect cube), and the latter two assessed participants' expectations about which object the hand was going to grasp.

Frequency of anticipations. With this score, we explored to what extent participants showed anticipations at all—regardless of the correctness of their anticipations. This was done to ensure that our stimuli triggered anticipatory looking to the cubes and to examine whether the age groups differed in their overall number of anticipatory fixations to either of the two cubes. Therefore, anticipations to a cube were coded as 1 and fixations somewhere else on the screen were coded as 0 (similar to Daum et al., 2012; Ganglmayer et al., 2020; Hunnius & Bekkering, 2010). Similarly, for the familiarization trials, anticipatory fixations to the single cube were coded as 1 and fixations somewhere else on the screen were coded as 0.

First fixation score. This measure assessed to which of the two goal AOIs participants fixated first after the hand had disappeared behind the occluder. This measure is well-established in the literature (Daum et al., 2012; Ganglmayer et al., 2020). For each trial, a first fixation to the correct cube (i.e., the cube the hand was going to grasp) was coded as 1 and a fixation to the incorrect cube was coded as 0. If participants showed no fixation to either goal AOI—that is, they fixated somewhere else on the screen or showed no fixation at all—this was treated as a missing value.

Differential looking score. This score represents the relative looking time to one goal AOI in relation to the other goal AOI. We included this measure to account for corrective eye movements given that participants might fixate first on one AOI but direct most of the following fixations to the other AOI

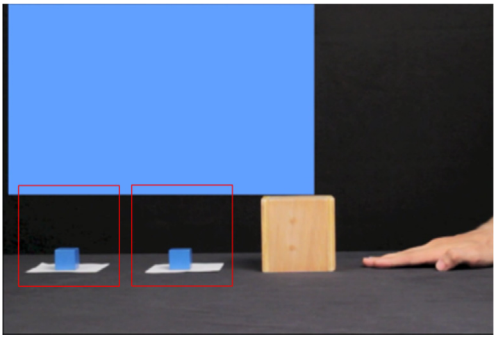

Fig. 3. Stimulus material of a test trial. The red boxes indicate the two goal areas of interest. (For interpretation of the reference to color in this figure legend, the reader is referred to the Web version of this article.). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(similar to Schuwerk & Paulus, 2016; Senju et al., 2009). The total looking time to the incorrect goal AOI was subtracted from the total looking time to the correct goal AOI and divided by the sum of total looking time to both goal AOIs. This resulted in scores ranging from −1 to 1, with a value toward −1 indicating a looking bias toward the incorrect cube and a value toward 1 indicating a looking bias toward the correct cube.

Analyses strategies

SPSS Statistics 24 (IBM Corp., Armonk, NY, USA) was used for statistical analyses. In addition, linear mixed models (LMMs) and binomial generalized linear mixed models (GLMMs) were run in R (Version 3.6.1) using the *lmer* and *glmer* functions of the "lme4" package.

Frequency of anticipations. To check whether participants anticipated the actions and whether age groups showed a comparable number of anticipations, a one-way ANOVA with age group as a between-participant factor was calculated for the familiarization and test trials using the averaged frequency of anticipations (averaged over the six trials in the familiarization phase and over the 10 trials in the test phase).

First fixations. To investigate our main question of whether anticipations (measured as first fixations) are based on kinematic cues and to check for differences among age groups, we performed a binomial GLMM with age group, condition (close or far), the interaction of age group and condition as fixed effects, participant as a random effect, and the first fixation score (0 or 1) as the outcome. To examine whether age groups showed a comparable number of correct anticipations in each condition, we ran further binomial GLMMs with age group as a fixed effect and participant as a random effect for each condition separately. To more precisely investigate the differences among age groups, we averaged the first fixation score over the five test trials and calculated a one-way ANOVA with age group as a between-participant factor. Bonferroni-corrected pairwise post hoc tests were conducted to determine which age groups differ in their averaged first fixation score. Moreover, two-sided *t* tests were run to test whether participants' first fixation bias toward one of the goal AOIs was different from chance.

Differential looking score. In addition to the first fixations, the relative time participants spent looking at one of the two goal AOIs was analyzed to examine whether participants based their anticipations on the kinematic cues. We ran a mixed ANOVA with condition (close or far) as a within-participant factor, age group as a between-participant factor, and the DLS averaged over the respective five trials as the outcome variable. To investigate whether participants' looking bias would differ significantly between the two categories and from chance level, we ran two-sided *t* tests for the age groups and categories separately.

Learning effects (DLS). To examine whether participants' looking bias (measured as DLS) over the trials varied between the two categories, we compared an LMM with condition and trial as fixed effects and participant as a random effect with an LMM including only trial as a fixed effect and participant as a random effect. Furthermore, LMMs were run for each age group and condition separately with participant as a random effect, trial as a fixed effect, and the DLS of each of the five trials as the outcome. To find out whether the looking behavior changed over the trials, these models were compared with LMMs that included only the random effect (participant) using likelihood ratio tests.

Results

Frequency of anticipatory looking

Familiarization trials. Participants anticipated in 295 of 588 trials (50.17%). Table 5 in the online supplementary material shows the frequency of anticipatory looking to the single cube for the six familiarization trials. To analyze whether age groups showed a different number of anticipations to the cube, we calculated an average score over the six trials. A one-way ANOVA with this score and age group as between-participant factors revealed a significant effect of age group, $F(3, 93) = 3.76$,

p = .013, η_p^2 = .11. Bonferroni-corrected pairwise comparisons revealed a significant difference between the adult group (*M*=.63, *SE*=.06) and 3-year-olds (*M*=.39, *SE*=.06), p = .013. The 4-year-olds (*M*=.54, *SE*=.06) and 10-year-olds (*M*=.56, *SE*=.04) did not differ significantly from 3-year-olds (p = .299 and p = .102, respectively). Moreover, 4-year-olds and 10-year-olds did not differ significantly from adults or from each other (all *p*s = 1.0). These analyses show that the stimulus material elicited a comparable number of first fixations to the single cube in all age groups, with only adults showing significantly more anticipations than 3-year-olds.

Test trials. Participants anticipated in 625 of 980 trials (63.77%). Table 6 in the supplementary material shows the descriptive statistics for the frequency of anticipatory looking for each trial, age group, and condition. To analyze whether age groups showed a different number of anticipations to either of the two cubes, we calculated an average score over the 10 test trials. A one-way ANOVA with this score and age group as between-participant factors revealed a significant effect of age group, $F(3, 94)$ = 11.45, p < .001, η_p^2 = .27. Bonferroni-corrected pairwise comparisons revealed that adults (*M*=.83, *SE*=.04) showed a significantly higher number of anticipations compared with 3-year-olds (*M*=.54, *SE*=.04), p < .001, and 4-year-olds (*M*=.62, *SE*=.05), p = .003. Moreover, 10-year-olds (*M*=.77, *SE*=.03) showed more anticipations than 3-year-olds (p < .001). There were no significant differences between 3-year-olds and 4-year-olds (p = 1.0), between 4-year-olds and 10-year-olds (p = .094), or between 10-year-olds and adults (p = .798). These analyses show that the two older age groups anticipated the cubes more often than the younger age groups. Data for this experiment and the second experiment are available at the Open Science Framework (OSF) (https://osf.io/m4x6h/?view_only=eaf5830aad7a40dba8039f5e208d3b5f).

First fixation score

To investigate our main question of whether anticipations are based on kinematic cues, we analyzed the first fixation score. Fig. 4 (top) shows the scores of first fixations averaged over the respective five trials for each age group and condition. A binomial GLMM with age group, condition (close or far), and the interaction of age group and condition as fixed effects, participant as a random effect, and the first fixation score (0 or 1) as the outcome was performed. The interaction of condition and age group turned out to significantly predict the first fixation score (b = 0.88, *SE*=0.29, z = 3.02, p = .002, odds ratio = 2.41, 95% confidence interval (CI) [1.38, 4.38]). Moreover, there was a significant effect of condition (b = −6.27, *SE*=0.90, z = −6.99, p < .001, odds ratio = 0.001, 95% CI [0.0002, 0.009]), whereas age group was not a significant predictor (b = −0.10, *SE*=0.26, z = −0.38, p = .701, odds ratio = 0.90, 95% CI [0.53, 1.49]).

To further investigate the interaction effect, binomial GLMMs with age group as fixed effects and participant as a random effect were run for each condition separately.

For the close condition, age group (b = −0.10, *SE*=0.31, z = −0.33, p = .743, odds ratio = 0.90, 95% CI [0.35, 0.87])[1] did not significantly predict the first fixation score. This indicates that over all trials, all age groups showed a comparable number of correct anticipations in the close condition. One-sample t tests against chance revealed that all age groups anticipated to the close cube above chance (Table 1).

For the far condition, on the other hand, age group (b = 0.85, *SE*=.19, z = 4.39, p < .001, odds ratio = 2.34, 95% CI [1.64, 3.57]) significantly predicted the first fixation score. Thus, we averaged the first fixation score over the five far trials and calculated a one-way ANOVA with age group as a between-participant factor. The ANOVA revealed a significant result for age group, $F(3, 89)$ = 9.13, p < .001, η_p^2 = .23. Bonferroni-corrected post hoc tests revealed significant differences between adults (*M*=.61, *SE*=.06) and all other age groups: 3-year-olds (*M*=.15, *SE*=.06), p < .001, 4-year-olds (*M*=.23, *SE*=.07), p = .001, and 10-year-olds (*M*=.30, *SE*=.06), p = .005. Child age groups did not perform significantly different from each other (all *p*s ≥ .400). This shows that in the far condition, adults anticipated to the correct far cube more often than the child groups. Except for adults, all one-sample t tests against chance level for all age groups were significant (Table 1), indicating that children's perfor-

[1] We used the often recommended profile method to estimate CIs. Please note that the 95% CI does not include the estimated value parameter. This might be due to the very uneven distribution of the dependent variable of this model. To stay consistent with the other analyses, we decided to report the profile CI also for this analysis.

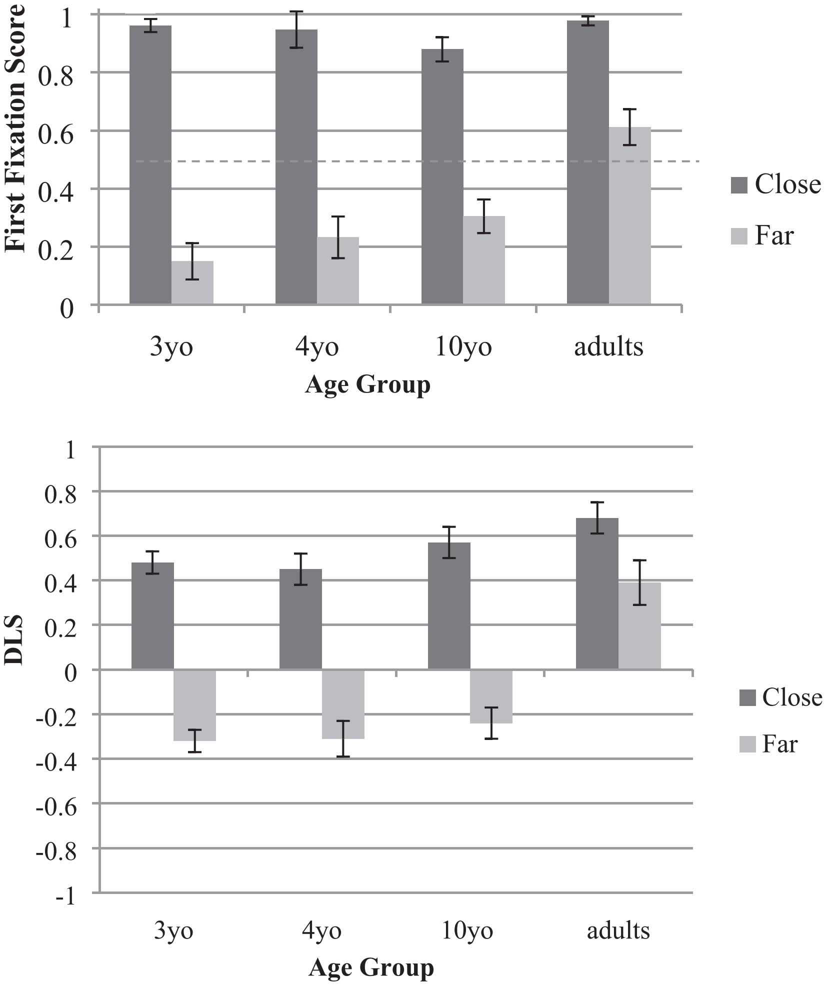

Fig. 4. First fixation score (top) and differential looking score (bottom) for each age group and condition. The dashed line represents chance level at.50 for the first fixation score. Error bars depict standard errors. yo, –year-olds.

Table 1
Results of the one-sample *t* tests against chance level for the first fixation score (chance level at .50) and differential looking score (chance level at 0) for each age group and condition.

	3-year-olds		4-year-olds		10-year-olds		Adults	
	t	*p*	*t*	*p*	*t*	*p*	*t*	*p*
First fixation score								
Close	20.53	<.001	8.50	<.001	9.10	<.001	30.63	<.001
Far	–5.60	<.001	–3.73	.002	–3.37	.002	1.81	.086
Differential looking score								
Close	8.90	<.001	6.10	<.001	8.41	<.001	10.19	<.001
Far	–6.12	<.001	–4.00	.001	–3.50	.002	3.86	.001

mance was significantly below chance level in the far trials. Hence, children rather showed first fixations to the incorrect close cube in the far condition, whereas only adults showed a tendency of looking toward the correct far cube even though being not significant.

Differential looking score

To account for corrective eye movements, for which the first fixation score does not account, the DLS was analyzed. Fig. 4 (bottom) shows the mean DLS for each age group and condition. The mixed ANOVA resulted in a significant interaction effect between condition (close or far) and age group, $F(3, 94) = 5.79$, $p = .001$, $\eta_p^2 = .16$. To further investigate this effect, paired-sample t tests for each age group between the far and close conditions were performed. All age groups performed significantly better in the close condition compared with the far condition [3-year-olds: $t(27) = 10.17$, $p < .001$; 4-year-olds: $t(19) = 7.49$, $p < .001$; 10-year-olds: $t(29) = 8.41$, $p < .001$; adults: $t(19) = 2.43$, $p = .025$].

A one-way ANOVA for the DLS of the close condition and age group as between-participant factor revealed no effect of age group, $F(3, 94) = 2.06$, $p = .110$, $\eta_p^2 = .06$, indicating that all four age groups performed similarly in the close trials. One-sample t tests against chance revealed that—similar to the first fixation score—all age groups anticipated the correct close cube above chance (Table 1).

An ANOVA for the DLS of the far condition resulted in a significant effect of age group, $F(3, 94) = 18.91$, $p < .001$, $\eta_p^2 = .38$. Bonferroni-corrected pairwise comparisons revealed a significant difference between adults (M=.39, SE=.10) and 3-year-olds (M= −.32, SE=.05) as well as between adults and 4-year-olds (M= −.31, SE=.08) and between adults and 10-year-olds (M= −.24, SE=.07), all ps < .001. As for the first fixation score, the child groups did not differ significantly from each other (all ps = 1.0). Thus, adults looked longer at the correct cube than the other age groups when the hand reached for the far object. One-sample t tests against chance for each age group revealed a similar pattern of results as for the first fixation score: Only adults showed a looking bias toward the correct far cube, whereas all child groups looked longer on the incorrect close cube.

Analyses of learning effects (DLS)

The DLS over the five trials for each age group and condition are depicted in Fig. 6 of the online supplementary material. An LMM with condition and trial as fixed effects and participant as a random effect (full model) was compared with a model including only trial as a fixed effect and participant as a random effect (reduced model). A likelihood ratio test revealed that the model that also included condition as a predictor matched the data significantly better [Akaike information criterion (AIC) reduced model = 1920.49, AIC full model = 1653.04, $\chi^2(1) = 269.45$, $p < .001$]. Thus, all further analyses were computed for the close and far conditions separately.

To test for learning effects over the five trials, LMMs with participant as a random effect, trial as a fixed effect, and DLS as the outcome were calculated (Table 2). Moreover, we compared a model including the random and fixed effects with a model including only the random effect for each age group and condition (likelihood ratio test in Table 2). For 10-year-olds in the far condition, the model also including trial as a predictor turned out to fit the data significantly better than the model including only participant as a random effect. None of the other model comparisons revealed a significant difference. This indicates that none of the age groups showed a change in looking bias over the five trials in the close condition and that only 10-year-olds showed a learning effect in the far trials. Nevertheless, 10-year-olds' DLS in the fifth trial (M=0.13, SE=0.16) was at chance level, $t(26) = 0.87$, $p = .393$. This indicates that even though 10-year-olds' looking bias toward the correct far cube increased over the five trials, these children still performed at chance in the last trial.

Discussion

The first experiment aimed at investigating whether kinematic cues allow anticipating the target of an observed action, as proposed by DMT and other simulation theories (e.g., Gallese et al., 2004; Rizzolatti et al., 2001; Rizzolatti & Sinigaglia, 2010), or whether action anticipations are rather based on lower-level perceptual mechanisms (Ganglmayer et al., 2019; Hunnius & Bekkering, 2014; Ruffman

Table 2
Results of the linear mixed models over the five trials for the differential looking score and of the likelihood ratio tests.

Age group	Condition	Intercept			Trial			Likelihood ratio test			
		β	*SE*	*t*	β	*SE*	*t*	AIC_{random}	AIC_{full}	χ^2	*p*
3-year-olds	Close	0.49	0.11	4.45	0.00	0.03	−0.10	185.33	187.32	0.01	.920
	Far	−0.49	0.10	−4.71	0.06	0.03	1.78	183.11	181.94	3.17	.075
4-year-olds	Close	0.46	0.13	3.57	0.00	0.04	−0.06	140.67	142.67	0.00	.949
	Far	−0.39	0.16	−2.47	0.03	0.05	0.57	177.46	179.13	0.32	.570
10-year-olds	Close	0.47	0.11	4.28	0.03	0.03	1.08	241.46	242.28	1.18	.277
	Far	−0.51	0.14	−3.62	0.09	0.04	2.22	319.57	316.70	4.88	.027
Adults	Close	0.56	0.11	5.12	0.04	0.03	1.42	121.71	121.70	2.01	.157
	Far	0.16	0.16	0.98	0.07	0.04	1.67	203.63	202.87	2.76	.097

Note. The likelihood ratio test compares a model including only the random effect (participant) with the full model including the fixed (trial) and random effect (participant). AIC, Akaike information criterion.

et al., 2012). To this end, participants watched a video in which the motor kinematics of a reaching movement varied depending on whether the actor grasped a close or far object. We assessed whether participants would use the motor kinematics to anticipate which of the two target objects the actor was going to grasp. Results of both key measures, the first fixation score and the DLS, provide evidence that only adults, but not 3- to 10-year-olds, base their anticipations on kinematic cues, speaking against DMT (at least for early and middle childhood). Instead, the findings support claims that action anticipations are rather based on early-developing perceptual mechanisms.

The key finding was that all child groups showed a strong looking bias toward the close cube in the far condition, indicating that they did not base their visual anticipations on the kinematic cues. Whereas the direct-matching and lower-level perceptual mechanism accounts make similar predictions for the close condition (i.e., anticipations to the close cube), the far condition constitutes a crucial test to differentiate between the two approaches. DMT predicts anticipations to the far object (based on the kinematic cues), whereas lower-level perceptual mechanisms predict anticipations to the close cube (based on anticipating the direction of the movement until coming across an object). Crucially, instead of using the motor kinematics to anticipate the target, children showed a looking bias toward the close cube in both conditions. Thus, the results speak against simulation theories, according to which observing an action allows simulating and consequently anticipating the action goal (e.g., Gallese et al., 2004; Goldman, 2006; Rizzolatti et al., 2001). Instead, children's looking bias toward the close cube—irrespective of the kinematic cues—supports claims that action anticipations are based on lower-level perceptual mechanisms. Observing the grasping movement elicited fixations to the close object. However, it did not allow for differentiating which of the objects the hand was going to grasp. Instead, children looked at the closer cube, presumably due to lower visual eccentricity. This reflects a central bias where more centrally presented stimuli are attended before peripheral stimuli (Staugaard et al., 2016). This gaze pattern was present in all child age groups.

Interestingly, 10-year-olds improved in anticipating the grasping of the far cube over the trials. Thus, observing the action repeatedly contributed to improvements in action anticipating. This points to the importance of statistical learning for visually anticipating others' actions (e.g., Ruffman, 2014; Ruffman et al., 2012). A more detailed discussion of this finding can be found in the General Discussion.

Two measures were used to assess action anticipations and, thus, to reveal participants' expectations about the actor's action: the first fixation score and the DLS. The first fixation score constitutes a more stringent measure of action anticipation in that it includes only the first anticipatory fixation to one of the two target objects. The DLS, on the other hand, considers all fixations during the anticipatory period and thus is also sensitive to corrective eye movements. Noteworthy, both measures showed a similar pattern of results. Thus, the results cannot be explained by an initially fast but inaccurate eye movement that is subsequently corrected. Instead, both measures indicate that children did not use kinematic cues for target anticipation.

Some alternative explanations are considered rather unlikely. First, participants were provided with no other information about the actor's goal than the kinematic cues. In particular, the single cube in the familiarization phase was located centrally between the two cubes of the testing phase. Thus, it is unlikely that the familiarization phase enhanced anticipations to either of the two objects. Second, the analyses of the frequency of anticipatory looking during the familiarization and test phases proved that the grasping movement elicited anticipatory fixations in all age groups. Although there were differences in the number of anticipatory fixations among age groups, even 3-year-olds anticipated the grasping actions. Thus, it is unlikely that children's looking bias toward the incorrect close cube in the far test trials can be explained merely by less overall anticipatory fixations in children compared with adults. Third, given that we presented the trial types in a pseudo-randomized order, it was clear that the protagonist was able to grasp for both objects. This renders it unlikely that participants thought that in the close condition the adult would not be able to grasp for the object more far away. Moreover, there were uneven numbers of participants per age group given that we had only specified a minimum number of participants. Therefore, we decided to apply a fixed stopping rule to Experiment 2.

Experiment 1 showed that 3- to 10-year-olds anticipate an object in the general direction of a grasping movement but do not base their anticipations on kinematic cues. This indicates that their anticipations are based on lower-level perceptual mechanisms rather than on matching the observed movement. Moreover, it suggests that kinematic cues are not processed automatically from early on in life. Stronger evidence that the processing of kinematic cues is not an automatic process but relies (at least initially) on slow and cognitively demanding processes would be provided by demonstrating that children use kinematic cues for action prediction before they use them for action anticipations. To examine this possibility, we conducted Experiment 2.

Experiment 2: Action prediction

Method

Participants

The final sample comprised 80 participants, 20 for each of four age groups: 3-year-olds (*M*=3;7; 11 girls), 4-year-olds (*M*=4;7; 9 girls), 10-year-olds (*M*=10;4; 11 girls), and adults (*M*=25;3; 11 women). Per age group, 20 analyzable participants served as a stop criterion for data collection. Due to an experimenter error, this criterion was neglected for the 10-year-olds. Thus, we excluded 15 additionally tested 10-year-olds to ensure comparable sample sizes across age groups.[2] An additional 11 participants were excluded due to providing too few trials (3-year-olds: n = 6), refusing to participate in the task (3-year-olds: n = 1), or technical issues (3-year-olds: n = 3; 4-year-olds: n = 1). Participants came from the same population as in Experiment 1, received the same compensation for participation, and gave informed consent about participation as described in Experiment 1. Ethic approval was obtained from the local ethics board.

Stimuli

Stimulus material was identical to that in Experiment 1.

Setting and procedure

Participants sat in front of a screen and were told that they were going to watch a movie. The procedure was identical to that of Experiment 1 and differed only in two crucial aspects. First, there was no eye tracking. Second, the experimenter stopped the video when the hand was behind the occluder and asked the participants to "Show me which cube the hand will grasp." Otherwise, the procedure remained the same so that after indicating which cube the hand was going to grasp, participants saw which cube the hand actually grasped.

[2] All analyses were also run including the 15 10-year-olds. There were no differences in the results except for the learning effects in the close condition over the first to fifth test trials as well as over the second to fifth test trials being now significant for the 10-year-olds.

Explicit prediction score

Each trial was coded as 1 if participants indicated the cube the actor was going to grasp and was coded as 0 if they indicated the wrong cube. Participants' verbal responses or pointing after being verbally asked were accepted as indicators. Trials in which participants pointed to any other location than to the target cubes or indicated that they did not know the answer were considered as invalid and excluded from the analyses (close—3-year-olds: 7%; 4-year-olds: 1%; 10-year-olds: 1%; far—3-year-olds: 2%; 4-year-olds: 3%). Because this was only a small proportion for all age groups, we did not further analyze differences in the general number of predictions.

Analyses strategy

We used the same programs and functions as in the first experiment. To analyze whether participants' predictions differed in the close trials compared with the far trials and to check for differences among age groups, a binomial GLMM with age group, condition (close or far), and the interaction of age group and condition as fixed effects, participant as a random effect, and the prediction score (0 or 1) as the outcome was performed. To further examine differences among age groups, we averaged the prediction score over all trials and performed a one-way ANOVA with age group as a between-participant factor and subsequent Bonferroni post hoc tests. By using one-sample *t* tests against chance, we tested whether the age groups predicted the correct and incorrect cubes differently from chance.

To statistically examine the learning effects over the five trials for each age group and condition, binomial GLMMs with participant as a random effect, trial as a fixed effect, and the prediction score (0 or 1) as the outcome were calculated. Given that participants did not know that they were going to be asked to predict the target of the action in the first trial, we reran the learning effect analyses for the second to fifth trials.

Results

Examining the data revealed one extreme outlier (below first quartile – 3*interquartile range) in the adult sample. This participant was excluded from further analyses.

Explicit prediction score

Fig. 5 shows the averaged explicit prediction scores over the respective five trials of each condition (close or far) and for each age group. A binomial GLMM with age group, condition (close or far), and the interaction of age group and condition as fixed effects, participant as a random effect, and the prediction score (0 or 1) as the outcome was performed. The interaction of condition and age group did not significantly predict participants' prediction score ($b = -0.09$, SE=0.20, $z = -0.44$, $p = .661$, odds ratio = 0.91, 95% CI [0.61, 1.36]). There was a main effect of age group ($b = 1.21$, SE=0.17, $z = 7.22$, $p < .001$, odds ratio = 3.36, 95% CI [2.46, 4.79]), but no main effect of condition ($b = -0.01$, SE=0.43, $z = -0.04$, $p = .971$, odds ratio = 0.98, 95% CI [0.42, 2.31]). Thus, we averaged the prediction score over all 10 test trials and ran a one-way ANOVA with age group as a between-participant factor to further examine the age group differences. The ANOVA confirmed the main effect of age group, $F(3, 75) = 85.41$, $p < .001$, $\eta_p^2 = .77$. Post hoc Bonferroni-corrected comparisons revealed that 3-year-olds (M=.52, SE=.03) and 4-year-olds (M=.50, SE=.04) performed significantly worse compared with 10-year-olds (M=.92, SE=.02) and adults (M=.96, SE=.02), all ps < .001. There was no statistically significant difference between 3-year-olds and 4-year-olds or between 10-year-olds and adults (both ps = 1.0). This indicates that over both categories the two younger child groups predicted the cube the hand was going to grasp significantly worse than 10-year-olds and adults.

One-sample t tests against chance (.50) for each age group revealed that neither 3-year-olds, $t(19) = 0.51$, $p = .613$, nor 4-year-olds, $t(19) = 0.13$, $p = .896$, performed differently from chance level. On the other hand, 10-year-olds, $t(19) = 24.37$, $p < .001$, and adults, $t(18) = 26.53$, $p < .001$, performed above chance.

In sum, the results show that only 10-year-olds and adults correctly predicted the cube the hand was going to grasp. There was no difference in predicting the close trials compared with the far trials.

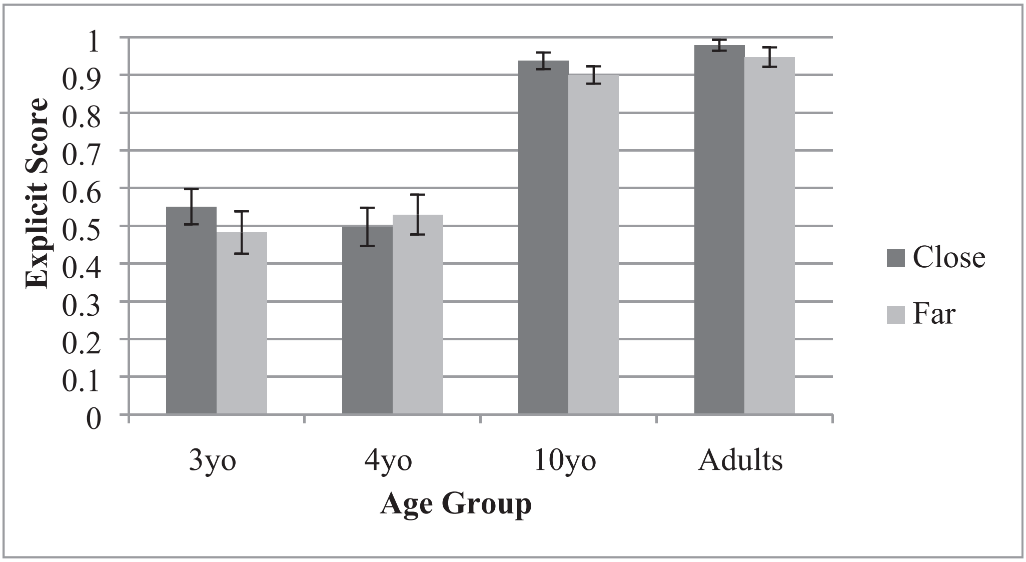

Fig. 5. Explicit close and far scores for the four age groups. Chance level was at.50. Error bars depict standard errors. yo, −year-olds.

Analyses of learning effects

The prediction scores over the five trials for each condition and age group are depicted in Fig. 7 in the supplementary material. To statistically examine learning effects over the five trials of each condition, binomial GLMMs with participant as a random effect, trial as a fixed effect, and the prediction score (0 or 1) as the outcome were calculated for each age group (Table 3). Trial turned out to be a significant predictor for 10-year-olds in the far condition. In the close condition, trial was marginally significant for 10-year-olds. None of the other age groups showed a change in correctly predicting the grasping movement over the five trials in either the close or far condition.

Post hoc analyses

Noteworthy, participants did not know that they were going to be asked to predict the target of the action in the first trial. Given that this might be crucial to trigger the explicit information processing system, we decided to further analyze the second to fifth trials.

To statistically test for performance changes over the second to fifth trials, further binomial GLMMs with the same variables as before were calculated (Table 4). Trial turned out to be a significant predictor for 4-year-olds' performance in the far condition, indicating a learning effect over the four trials. In the close condition, trial was marginally significant for 4-year-olds. Except for 4-year-olds, none of the other age groups showed a learning effect in either the close or far condition over the second to fifth trials.

Discussion

To investigate whether 3- to 10-year-olds and adults use kinematic cues to explicitly predict others' actions, we repeated Experiment 1 with one crucial change: This time we asked participants to predict which cube the hand was going to grasp. Importantly, even in this context, 3- and 4-year-olds did not use kinematic cues to predict the action. However, 10-year-olds used the kinematic cues to correctly predict the target object, whereas they did not correctly anticipate the target object in the first experiment. This suggests that children use kinematic cues for explicit action prediction before using them for action anticipations. Thus, using kinematic cues to predict others' actions seems

Table 3
Results of the generalized linear mixed models over the five trials for each condition and age group.

		Intercept				Slope				
Age group	Condition	β	*SE*	*z*	*p*	β	*SE*	*z*	*p*	R^2
3-year-olds	Close	−0.36	0.49	−0.74	.461	0.19	0.15	1.24	.214	.02
	Far	0.34	0.50	0.68	.497	−0.14	0.15	−0.95	.344	.07
4-year-olds	Close	−0.52	0.48	−1.08	.282	0.16	0.14	1.14	.254	.02
	Far	−0.22	0.48	−0.45	.653	0.09	0.14	0.64	.524	.00
10-year-olds	Close	0.88	0.87	1.01	.311	0.77	0.40	1.93	.054	.26
	Far	0.01	0.72	0.02	.987	0.93	0.35	2.68	.007	.35
Adults	Close	2.40	1.43	1.68	.092	0.58	0.61	0.95	.343	.17
	Far	3.40	2.51	1.35	.177	3.05	1.82	1.67	.094	.96

Table 4
Results of the generalized linear mixed models over the second to fifth trials for each condition and all age groups.

		Intercept				Slope				
Age group	Condition	β	*SE*	*z*	*p*	β	*SE*	*z*	*p*	R^2
3-year-olds	Close	−0.99	0.80	−1.23	.217	0.34	0.22	1.56	.117	.04
	Far	−0.81	0.79	−1.02	.307	0.15	0.21	0.69	.489	.06
4-year-olds	Close	−1.15	0.76	−1.85	.064	0.39	0.21	1.88	.061	.05
	Far	−2.02	0.81	−2.49	.013	0.54	0.22	2.48	.013	.10
10-year-olds	Close	0.77	1.88	0.41	.681	0.81	0.66	1.22	.224	.20
	Far	0.72	1.62	0.45	.654	0.71	0.55	1.29	.195	.16
Adults	Close	2.96	3.08	0.95	.340	0.42	0.97	0.44	.660	.06
	Far	2.94	3.08	0.95	.340	0.42	0.97	0.44	.660	.06

to require—at least initially—some explicit reasoning, indicating that it is a rather effortful and slow process.

Interestingly, 4-year-olds and 10-year-olds showed a learning effect over the trials. Whereas 10-year-olds' learning effect was present over the first to fifth trials, it was not significant anymore over the second to fifth trials, suggesting that it can be traced back to the increase in performance between the first and second trials. This indicates that the explicit reasoning after the first test trial was crucial for 10-year-olds' increase in prediction performance. The results showed a slightly different pattern for 4-year-olds. The 4-year-olds seemed to rely on the repeated visual feedback about which cube the actor grasped and adapted their predictions accordingly over time. Thus, 4-year-olds learned to use the kinematic cues to predict the target over the trials. This suggests that by age 4 children can learn to use kinematic cues to predict others' actions.

It might be argued that language deficits along with deficits in understanding the task in the younger age groups account for children's poor performance. We consider this unlikely. First, numerous other studies have shown that children are able to verbally predict actions by 3 years of age (e.g., Paulus et al., 2017; Wellman & Woolley, 1990). Second, in the current experiment all age groups predicted the grasping movement in the vast majority of the trials (even though those were mostly incorrect). Only few invalid trials needed to be excluded from the analyses. This indicates that already 3-year-olds were engaged in predicting the grasping action but that they were just not able to take the motor kinematics into account.

General discussion

One key question concerns how children come to understand and predict others' behavior (e.g., Carpendale & Lewis, 2004; Hunnius & Bekkering, 2014; Uithol & Paulus, 2014). Simulation theories have claimed that we understand others and anticipate their behaviors by activating mental processes that would evoke similar behaviors in ourselves. Consequently, it has been argued that simulating others constitutes the basis of early social cognition. One approach, the direct-matching theory of action understanding, claims that we understand others' actions by matching an observed action onto our own motor repertoire (Gallese et al., 2004; Rizzolatti et al., 2001; Rizzolatti & Sinigaglia, 2010) and that children are then able to anticipate an action if they master the action themselves (Falck-Ytter et al., 2006; Kanakogi & Itakura, 2011). Others have suggested that action anticipations are based on a range of perceptual mechanisms such as the recognition of visuospatial and statistical regularities (e.g., Ruffman et al., 2012), leading to an ongoing debate about the underlying mechanisms of action anticipation (Ganglmayer et al., 2019; Hunnius & Bekkering, 2014; Paulus, 2012). The current study contributes to this debate by showing that 3- to 10-year-olds do not use kinematic cues to anticipate the target of an action but instead anticipate the nearest object placed in the general movement direction of the grasping hand. Thus, the results speak against DMT, according to which kinematic cues play a special role in action understanding and allow anticipating the action target. Instead, the findings provide evidence for claims that action anticipations are based on perceptual mechanisms. This is discussed in more detail in the following paragraphs.

Perceptual processes underlie action anticipation

As shown in Experiment 1, only adults, but not 3- to 10-year-olds, based their visual anticipations on kinematic cues. According to DMT, others' actions are predicted by matching an observed action onto one's own motor repertoire (Gallese et al., 2004; Rizzolatti et al., 2001; Rizzolatti & Sinigaglia, 2010). In turn, having a motor representation of a certain action allows for anticipating the action when observing someone else performing it. By 3 years of age, children can reach and grasp objects. Even infants and toddlers show different motor kinematics during reaching and grasping actions, depending on the location and characteristics of the target objects as well as on the to-be-performed action (Chen et al., 2010; Claxton et al., 2003; Gottwald et al., 2017; Zaal & Thelen, 2005). For example, Gottwald et al. (2017) showed that the longer the distance between a to-be-grasped object and its target location, the slower infants' initial reaching toward the to-be-grasped object. Given this set of findings, it is very unlikely that children by age 3 did not have the respective motor representations of the observed actions. Nevertheless, 3- to 10-year-olds were not able to use the kinematic cues to anticipate the target object, speaking against the strong claims of DMT and other simulation accounts.

There is a recent debate about whether visual anticipations might rather be based on perceptual mechanisms such as statistical and associative learning (Daum et al., 2012; Ganglmayer et al., 2019; Hunnius & Bekkering, 2014; Ruffman et al., 2012). Moreover, gaze shifts can be triggered by non-foveal retinal stimulation (Harris, 1989), and more centrally presented stimuli are attended before peripheral stimuli (Wolfe et al., 1998). The current study supports these views by showing that children anticipate the first object they come across when following the general direction of the grasping movement—irrespective of the specific kinematic cues. By 3 years of age, children have observed many grasping movements, and by extracting regularities across several observations they might have learned that a grasping movement usually continues in its initial direction and is directed at an object. Thus, observing a grasping movement evokes anticipations to the first (i.e., the nearest) object they come across when following the movement direction. Related evidence for this explanation comes from computational models suggesting that the recognition of biological movements is based on learned prototypical visual patterns (Giese & Poggio, 2003).

To what extent different types of experience are crucial to elicit anticipations remains to be seen in future studies. Indeed, it might be that the anticipations found in the current study can be explained by even more simple mechanisms of non-foveal retinal stimulation (Harris, 1989). Importantly, there is first empirical evidence supporting this view given that an equivalent default strategy has been found in adults. When anticipating unpredictable grasping actions, adults anticipated toward a closer object compared with a farther away object (Rotman et al., 2006).

In any case, anticipating the nearest object in the movement direction is an efficient strategy because it is "on the way" to the following objects anyway. Thus, shifting gaze to the next object only if the currently fixated object is not located in the movement direction anymore (e.g., the grasping hand has passed the nearest object) allows for short distanced gaze shifts while avoiding missing potential targets.

Interestingly, 10-year-olds showed a learning effect of anticipating the grasping of the far object over the trials. Thus, repeated observations might eventually lead to associations between motor kinematics of specific reaching movements (e.g., reaching for a close vs. far object) and the location at which the grasping is directed. This points to an important role of statistical learning in action anticipation (Monroy et al., 2017, 2018; Paulus et al., 2011) and relates to claims of its role as a domain-general learning mechanism (Kirkham et al., 2002, 2007). Taken together, our findings support theoretical views suggesting that perceptual mechanisms seem to play an important role for visual action anticipations, particularly in early development, whereas kinematic cues seem less relevant.

Importantly, such perceptual processes might also account for the results of previous anticipation studies. Some scholars have also claimed that motor activation during action observation is not a prerequisite for action understanding but rather follows action interpretation, speaking against simulation accounts (Pomiechowska & Csibra, 2017). However, perceptual explanations have often been neglected in favor of interpretations based on simulation accounts (e.g., Falck-Ytter et al., 2006; Kanakogi & Itakura, 2011). For example, Falck-Ytter et al. (2006) showed that 12-month-olds and adults, but not 6-month-olds, visually anticipate a bucket in which an actor is about to place a toy. They concluded that their findings support DMT given that only 12-month-olds and adults, but not 6-month-olds, master such an action themselves and therefore were able to anticipate the target of the action. However, participants were presented with a single highly salient target object (a red bucket with a three-dimensional happy face connected to it) in the direction of the placing movement of the hand. Thus, the alternative explanation that participants followed the general direction of the placing movement and anticipated the only available object that was placed within this region is an equally likely explanation. The current study overcomes this limitation and shows that action anticipations are not based on mirroring motor kinematics but rather are explained by perceptual mechanisms.

Thus, our study comes to different conclusions than previous work that claimed evidence for young children's processing of kinematic cues (e.g., Ambrosini et al., 2013; Filippi & Woodward, 2016; Stapel et al., 2015). Potentially, perceptual processes could explain these results. For example, as discussed in the Introduction, Filippi and Woodward (2016) presented 13-month-olds with six identical trials of a grasping action that had either a congruent hand shape or an incongruent hand shape with respect to the target (matching or not matching the orientation of a to-be-grasped rod). Notably, given that participants watched exactly the same grasping in all six trials, they might have learned which object the hand was going to grasp. This would rather speak for the role of perceptual processes and statistical learning. In addition, mere matching of perceptual features—here the similarity of hand orientation and target orientation—might have facilitated the process. Future research needs to disentangle the processes subserving young children's action anticipation in greater detail.

Explicit action prediction precedes visual action anticipation

Many studies have used action anticipation and other nonverbal measures to examine the early development of understanding others' actions (Cannon & Woodward, 2012; Daum et al., 2012; Falck-Ytter et al., 2006; Gredebäck et al., 2009; Monroy et al., 2020). This line of research has led to the predominant view that children show an implicit understanding of others' actions before being able to verbally reason about others' actions. However, recent studies indicate that this is not necessarily the case. Predicting others' actions sometimes precedes correctly anticipating the same action (e.g., Paulus et al., 2017; Schuwerk & Paulus, 2016). These findings have fueled an ongoing debate about whether different processes might underlie the accomplishment of implicit and explicit action understanding (Barone et al., 2019; Grosse Wiesmann et al., 2017; Paulus et al., 2017). Our study contributes to this debate by demonstrating that kinematic cues are initially used in verbal action prediction rather than for visual action anticipation. The results question claims that action understanding always advances from an implicit level to an explicit level.

Specifically, 10-year-olds used kinematic cues to verbally predict the action target, and 4-year-olds learned to do so over the trials, whereas neither of the age groups used kinematic cues to correctly anticipate the action in the first experiment. Thus, kinematic cues are earlier used for explicit action predictions before being used for action anticipations. This is interesting in two ways. First, it shows that children's inability to use kinematic cues in the first experiment is not due to the nature of the used kinematic cues. In other words, the kinematic cues provided sufficient information to enable participants to form an expectation about which of the two cubes the hand was going to grasp. Second, and even more important, the findings suggest that kinematic cues are not processed automatically from early on in life, as would be expected by DMT (e.g., Gallese et al., 2004; Rizzolatti et al., 2001). Instead, the development of the use of kinematic cues seems to initially rely on rather cognitively demanding and slow processes. That is, akin to the mastery of other abilities such as correctly driving a car and learning how to read and write, an appreciation of kinematics might first demand to reason about others' behavior before it becomes a quick and automatized ability as assessed by eye tracking. This finding might be relevant for theories proposing that two systems underlie social information processing (e.g., Apperly & Butterfill, 2009; Strack & Deutsch, 2004) and challenges the predominant view that children generally show an implicit understanding of others' actions before showing an explicit understanding. Whereas previous research indicated that sometimes children are able to predict another's action before they correctly anticipate the same action (Paulus et al., 2017), the current study extends this to children's use of kinematic cues.

Overall, it seems to be common sense that the capacities for so-called implicit forms of understanding (e.g., visual anticipations) develop earlier than the explicit verbal forms of understanding (e.g., verbal reasoning)—given that the development of language capitalizes on nonverbal forms of communication (e.g., Bates et al., 1975). Yet, this does not justify the claim that this developmental sequence is true for every content or domain of knowledge or understanding. Some aspects of human behavior might first be understood on the level of reasoning before the knowledge translates into other forms of understanding (e.g., anticipations). Potentially, this might be true for an appreciation of subtle cues of kinematics as well.

Learning to anticipate and to predict

Finally, considering the learning effects across both experiments, it is noteworthy that the 3-year-olds showed no learning. When assessing visual anticipations (Experiment 1), the 10-year-olds showed learning, but the 3-year-olds and 4-year-olds did not. When asking participants verbally and thus stimulating children to think about the situations, the 4-year-olds were able to improve their performances. This relates well to theoretical views according to which children's reflection ability appears in a domain-general fashion at around age 4 (Allen et al., 2018, 2021). The verbal question in Experiment 2 led children to reflect about the observed actions and identify the kinematic cues as being relevant. In Experiment 1, without guidance by language, it was only the older children who could reflect on the actions and single out the kinematics as being relevant. It would be interesting to study in greater detail how the ability to reflect supports the development of different facets of action understanding.

Limitations and conclusions

Despite the interesting findings, the current study also has some limitations. We focused on four age groups with (partially) considerable age differences. This was based on theoretical considerations that an assessment of these age groups would be particularly informative. Our results revealed a significant improvement between 4 and 10 years of age when verbally predicting others' grasping actions and after 10 years of age when visually anticipating such actions. This calls for future empirical work that focuses specifically on these age ranges.

Moreover, to avoid an interaction of action anticipations and action predictions, we ran the two experiments with separate samples. It could be interesting to examine the interplay of action anticipations and predictions in more detail in future studies. Noteworthy, a recent study found that the implicit and explicit systems seem to inform each other by 3 years of age (Paulus et al., 2017). Whether an explicit instruction like "Which hand is the actor going to grasp?" might strengthen learning effects in visual anticipations remains an open question for further research.

In addition, from a theoretical point of view, it should be noted that we focused on two distinct forms of understanding others' actions: visual anticipations and responding to language as forms of implicit and explicit understanding. As for any categorical distinction, there are intermediate cases that are difficult to assign to one category. For example, imitation has been argued to demonstrate action understanding because the way in which one imitates the other reveals how the other's action was processed. If imitation happens as a response to a verbal request, one could wonder how to characterize this form of knowledge.

Finally, there are many theories that assign a role to simulation or mirroring processes in the processing of others' action (e.g., Goldman, 2006; Heyes, 2010; Paulus, 2012; Uithol et al., 2011). These theories differ considerably from each other. Some regard simulation as a process in which an insight into others' mental states is achieved and assign a special role to it (Goldman, 2006), whereas others conceive of it in terms of sensorimotor processes that do not come with any cognitive or conceptual understanding of others and/or regard it as only one among other perceptual processes (Paulus, 2012). From a perceptual point of view, differences in hand shape might be easier to detect and therefore children might learn earlier about the relevance of hand shapes than about the more transient nature of kinematics. The current study provides a critical view on the former claim that assigns a special role to simulation, but it does not exclude that simulation takes place—albeit as one process included in a host of other sensorimotor processes.

Taken together, the current study adds to two ongoing debates: first, whether different processes underlie visual action anticipations and verbal action predictions and, second, whether action anticipations are based on lower-level perceptual mechanisms rather than on simulating others' actions. We showed that children use kinematic cues first to predict others' actions before using them to anticipate others' actions. This suggests that the use of kinematic cues requires—at least initially—some explicit reasoning, indicating that it is a rather cognitively demanding and slow process. Furthermore, children did not base their anticipations on the specific motor kinematics of the observed actions. This provides evidence that action anticipations are guided by lower-level perceptual mechanisms rather than by simulating others' actions.

CRediT authorship contribution statement

Saskia Melzel: Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nicole Altvater-Mackensen:** Writing – review & editing, Supervision, Methodology. **Kerstin Ganglmayer:** Writing – review & editing, Investigation, Data curation. **Fabian Müller:** Methodology, Investigation, Conceptualization. **Konstantin Steinmassl:** Writing – review & editing, Visualization, Data curation. **Petra Hauf:** Writing – review & editing, Supervision, Conceptualization. **Markus Paulus:** Writing – original draft, Supervision, Funding acquisition, Conceptualization.

Data availability

Data are shared.

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Data availability

The data that support the findings of this study as well as the analysis code are openly available at the OSF (https://osf.io/m4x6h/?view_only=eaf5830aad7a40dba8039f5e208d3b5f).

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jecp.2024.106064.

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