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Infants' Goal Prediction for Simple Action Events: The Role of Experience and Agency Cues

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Abstract

Looking times and gaze behavior indicate that infants can predict the goal state of an observed simple action event (e.g., object-directed grasping) already in the first year of life. The present paper mainly focuses on infants' predictive gaze-shifts toward the goal of an ongoing action. For this, infants need to generate a forward model of the to-be-obtained goal state and to disengage their gaze from the moving agent at a time when information about the action event is still incomplete. By about 6 months of age, infants show goal-predictive gaze-shifts, but mainly for familiar actions that they can perform themselves (e.g., grasping) and for familiar agents (e.g., a human hand). Therefore, some theoretical models have highlighted close relations between infants' ability for action-goal prediction and their motor development and/or emerging action experience. Recent research indicates that infants can also predict action goals of familiar simple actions performed by non-human agents (e.g., object-directed grasping by a mechanical claw) when these agents display agency cues, such as self-propelled movement, equifinality of goal approach, or production of a salient action effect. This paper provides a review on relevant findings and theoretical models, and proposes that the impacts of action experience and of agency cues can be explained from an action-event perspective. In particular, infants' goal-predictive gaze-shifts are seen as resulting from an

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interplay between bottom-up processing of perceptual information and top-down influences exerted by event schemata that store information about previously executed or observed actions.

Keywords: Action events; Infant action-goal prediction; Infant gaze behavior; Eye tracking; Feedforward processes; Perception of agency cues

1. Introduction

The ability to predict the goal states and typical consequences of own and others' behaviors is crucial for human survival, because it allows the individual to adapt her own behavior to own and others' goals, for instance in cooperative or competitive situations. For simple actions (such as grasping for an object), the important cognitive ability of action-goal prediction seems to emerge already during the first year of life, but the underlying mechanisms are not completely understood (see Gredebäck & Falck-Ytter, 2015). Typical findings imply an important role of motor development and action experience, because infants can predict the goals of familiar simple actions that they can already perform themselves (e.g., grasping a toy) and for familiar agents (e.g., a human hand) at an earlier age than for unfamiliar actions (e.g., touching a toy with the back of the hand) or unfamiliar agents (e.g., a mechanical claw; Adam et al., 2016; Kanakogi & Itakura, 2011). Yet infants sometimes predict goals of simple actions of mechanical agents when those exhibit behavioral cues signaling agency, such as self-propelled movement or the production of a salient action effect (e.g., Adam & Elsner, 2018; Adam, Reitenbach, & Elsner, 2017). This paper summarizes the main findings and the theoretical accounts that seek to explain the underlying cognitive mechanisms in the development of infants' ability to perform predictive gaze-shifts to the goals of simple actions of human or mechanical agents. In particular, we will propose that an action-event perspective allows for integrating the roles of experience and agency cues for infants' action-goal prediction.

2. Defining actions and action events

An action is a movement performed by an agent to obtain a desired goal or endstate (e.g., Prinz, 1997). Thus, a simple action fulfils the definition of an event as being "a segment of time [...] that is conceived by an observer to have a beginning and an end" (Zacks & Tversky, 2001, p. 17), and it shows the common features of an event: Actions expand in time, are directed toward a goal, and involve animate, often human, agents (Zacks, Speer, Swallow, Braver, & Reynolds, 2007). In general, action events have a tripartite structure: (a) an initial state of the agent (e.g., visual features, spatial location, configuration of action-relevant body limbs) and the environment (e.g., presence of a target object); (b) a dynamic phase in which the agent performs a movement, thereby changing the initial state; and (c) a goal state that entails a perceivable target location and/or action effect and that may be the initial state for a subsequent action event (Butz, 2016; Otte, Schmitt, Friston, & Butz, 2017). Following the theory of event coding (Hommel, Müsseler, Aschersleben, & Prinz, 2001), action events are cognitively represented as bundles of perceivable features that include motor commands and interoceptive somatosensory feedback for own movements, and exteroceptive feedback (i.e., visual or auditory features) for own and others' actions.

For prediction, it is important that changes within an event come with high transitional probabilities. In contrast, goal states indicate event boundaries, which entail low transitional probability and larger prediction uncertainty (e.g., Baldwin, 2002; Baldwin & Baird, 2001). It is advantageous to shift gaze or visual attention toward the goal of an observed or self-performed action while the movement is still unfolding, because this enables to monitor the upcoming action effects, to plan ahead for probably following behaviors, and to infer the intentions that have motivated this behavior (Gredebäck & Daum, 2016). Several authors have proposed that event prediction relies on interactions of bottom-up information about perceivable event features and their statistical regularities with top-down influences exerted by event schemata (e.g., Zacks et al., 2007). The latter are semantic memory representations that store shared features of previously encountered events, including information about the sequential structure of activity. Top-down influences gain relevance for event prediction when the amount or quality of perceptual input (bottom-up) is poor and/or when transitional probabilities of changes are unknown (e.g., Butz, 2016). For infants, performing a predictive gaze-shift toward the goal of an ongoing action is quite challenging (Gredebäck & Daum, 2016), but there is evidence that this important ability develops already during the first year of life.

3. Measuring infants' evaluation and prediction of others' action goals

Infants' ability to form expectations about action goals can be assessed by measuring looking times to a motionless display of the goal state after the action had been completed. In a seminal study, 5-, 6-, and 9-month-olds repeatedly observed a human hand reaching for and grasping always the same out of two toys (Woodward, 1998). Here, infants could form a goal expectation involving the final spatial position of the agent (i.e., extrapolation of movement kinematics: hand at left/right target location) and/or the achieved action effect (i.e., expected constellation of perceivable features: hand grasping toyA/toyB). Then, positions of the target objects were swapped, and infants' looking times were measured to the motionless goal state of test events that showed the hand reaching for and grasping either the other toy at the familiar target location (i.e., change-of-goal) or the familiar toy at the other location (i.e., change-of-path). By 6 months, looking times were longer for change-of-goal than change-of-path, which was taken to indicate that infants had formed an expectation regarding the action goal, but not for merely the movement kinematics. Because looking times were obtained when complete action-event information had been provided, and when infants could take up to several seconds to detect the (mis)match between the attained goal state and their goal expectation, these measures assess mainly offline goal evaluation (Gredebäck & Daum, 2016).

Online action-goal prediction is mostly measured via eye tracking, recording infants' gaze-shifts during the unfolding of an action event (e.g., Gredebäck & Falck-Ytter, 2015; Gredebäck, Johnson, & von Hofsten, 2010). Infants see repetitions of a simple goal-directed action, such as a human hand reaching for and grasping a toy (Fig. 1). Depending on whether the infant's gaze arrives at the target object before, simultaneously with, or after the agent had contacted the target object, gaze is coded as predictive gaze-shift, as tracking gaze, or reactive gaze (e.g., Adam & Elsner, 2018). To ensure that the data reflect movement processing, many studies require the infant to look at the moving agent (e.g., for 200 ms) prior to the gaze-shift. Dependent measures are either the frequency of predictive gaze-shifts across several trials (e.g., Cannon & Woodward, 2012) or mean gaze-arrival times, calculated as time when gaze arrives at target minus time when agent arrives at target (e.g., Falck-Ytter, Gredebäck, & von Hofsten, 2006; Kanakogi & Itakura, 2011). To perform a predictive gaze-shift, infants have to process the relevant information within several hundreds of milliseconds, and they need to disengage their gaze from the interesting moving agent at a time when the information about the action event is still incomplete (Gredebäck & Daum, 2016). Therefore, online action-goal prediction is cognitively more demanding, and emerges later during infancy, than offline goal evaluation (e.g., Daum, Attig, Gunawan, Prinz, & Gredebäck, 2012). Some authors even doubt infants' ability for flexible online goal prediction (e.g., Ganglmayer, Attig, Daum, & Paulus, 2019). If we assume that infants succeed in online goal prediction, they probably need to tap on their experience with the observed action in order to overcome their limited processing capacities (e.g., Cannon & Woodward, 2012; Gredebäck & Falck-Ytter, 2015; Kanakogi & Itakura, 2011).

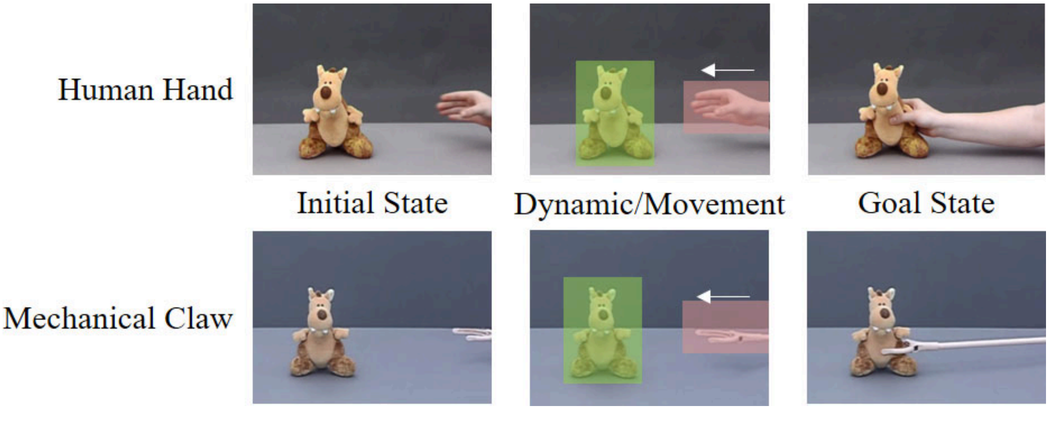

Fig. 1. Still frames of simple grasping events (lower line: adapted from Adam & Elsner, 2018). The colored rectangles (not presented to infants) indicate the positions of areas of interest (AOIs) for gaze analyses: green, goal AOI; red, agent AOI.

4. The impact of action experience: Familiar agents, familiar actions

In offline measures for infants' goal evaluation, 6- and 9-month-olds showed the looking-time pattern indicating formed goal expectations when observing an action that they could perform themselves (e.g., a human hand grasping a toy; Woodward, 1998), but not for an unfamiliar action that they rarely perform or observe (e.g., touching a toy with the back of the hand; Woodward, 1999). Furthermore, 7- and 12-month-olds did not form goal expectations when toy grasping was performed by an unfamiliar agent (e.g., wooden rod or gloved hand), unless having seen the gloved hand belonging to a person (Guajardo & Woodward, 2004).

Similarly, in online measures for infants' action-goal prediction, 12-month-olds and adults showed predictive gaze-shifts when observing a human hand transporting a ball into a bucket, but reactive gaze when the ball moved into the bucket on its own, with self-propelled biological motion or rigid mechanical motion. Thus, 12-month-olds were able to predict the goal state from seeing the initial state and the beginning of the movement, but only for the human hand, which is a familiar agent regarding both self-performed and observed actions. However, infants could not do that at 6 months, when the observed human toy-transporting is still unfamiliar because infants have only recently (at about 5 months) achieved the motor-development milestone of visually guided grasping (Gredebäck & Falck-Ytter, 2015; see also Gredebäck, Lindskog, Juvrud, Green, & Marciszko, 2018; Kanakogi & Itakura, 2011).

Familiarity of the agent was also relevant when 9- to 12-month-olds performed goal-predictive gaze-shifts for a toy-grasping action of a human hand, but reactive gaze for the same familiar action of a mechanical claw (Fig. 1; Adam et al., 2016; Cannon & Woodward, 2012; Kanakogi & Itakura, 2011). Regarding the familiarity of the action, infants between 6 and 16 months did not generate predictive gaze-shifts when observing an unfamiliar back-of-hand toy-touching action (Kanakogi & Itakura, 2011; Krogh-Jespersen & Woodward, 2014). Moreover, 12-, but not 6-month-olds who observed feeding with a spoon performed predictive gaze-shifts to the mouth, with positive correlations to their experience of being fed (Gredebäck & Melinder, 2010). There were also positive correlations between 6-month-olds' prospective motor control and their online goal prediction of others' eating actions (Gredebäck et al., 2018), between 12-month-olds' engagement in containment actions and their subsequent goal prediction for observed human containment actions (Cannon, Woodward, Gredebäck, von Hofsten, & Turek, 2012), and between 12-month-olds' abilities to perform and to predict contralateral reaching movements (Melzer, Prinz, & Daum, 2012).

To explain these findings, some theoretical models (named *experience-based accounts* by Bíró & Leslie, 2007) proposed a link between infants' ability for online goal prediction and their active experience in executing the observed action (e.g., Cannon & Woodward, 2012; Falck-Ytter et al., 2006; Kanakogi & Itakura, 2011). Some of these accounts highlight the relevance of the mirror-neuron system (MNS), which is active during action execution and action observation (e.g., Rizzolatti, Fadiga, Gallese, & Fogassi, 1996), and which can enable goal prediction via direct matching of the observed action features to a corresponding motor representation (e.g., Falck-Ytter et al., 2006; Gredebäck & Falck-Ytter, 2015; Gredebäck et al., 2018; Kanakogi & Itakura, 2011; Rizzolatti, Fogassi, & Gallese, 2001). Other accounts claim that goal prediction becomes possible when infants can map the intentional or goal structure of others' actions to their own action experience, which then allows for a prediction of the kinematic aspects and the goal state of the movement (Cannon & Woodward, 2012; Gerson & Woodward, 2014). Experience-based accounts therefore assume that online goal prediction is only possible for familiar agents and actions.

First evidence for direct matching came from an eye-tracking study that found highly similar patterns of goal-predictive gaze-shifts when adults performed and when they observed someone else perform a block-stacking task (Flanagan & Johansson, 2003). Action execution and action observation probably activate similar motor programs, which include instructions for the visual system to produce goal-predictive gaze-shifts (e.g., Gredebäck & Falck-Ytter, 2015). Likewise, infants' predictive gaze-shifts usually emerge when motor development allows for the execution of the observed action (e.g., Cannon et al., 2012; Falck-Ytter et al., 2006; Gredebäck & Melinder, 2010; Kanakogi & Itakura, 2011). Fittingly, offline measures revealed that active training with certain actions fosters infants' ability to form goal expectations for observed action events. Three-month-olds who still lacked grasping experience showed the respective looking-time pattern for a human grasping action, but only after a short training in which infants had picked up Velcro-covered objects with "sticky" mittens (Sommerville, Woodward, & Needham, 2005). Active training is more effective for subsequent offline goal evaluation than is merely observing another person's actions (Gerson & Woodward, 2014). Although such findings support experience-based accounts, other studies suggest that there is more to infants' action-goal prediction than direct matching.

5. The impacts of target-object size and feedforward processes

Further evidence for parallels in the development of goal-predictive processes in action execution and action observation comes from influences of the target object's size on infants' online goal prediction. When observing a reaching hand, shaped in a whole-hand grasp, together with two target objects, one large and one small, adults and 6-, 8-, and 10-month-old infants performed predictive gaze-shifts toward the large target object (Ambrosini, Costantini, & Sinigaglia, 2011; Ambrosini et al., 2013). However, when the hand was shaped in a precision grasp, only adults and 10-month-olds gazed predictively at the small target object, indicating that these participants used information about grasp aperture for online goal prediction. Adults' pre-shaping of their hand when reaching for differently sized target objects is taken as a hallmark example for feedforward motor control, guided by the target object's visual features (e.g., Desmurget & Grafton, 2000). Corresponding to the age differences in infants' predictive gaze-shifts, active hand pre-shaping is present for whole-hand grasps toward large target objects at an earlier age (*c.*

9 months) than for precision grasps toward small target objects (starting from 11 months; Zaal & Thelen, 2005). Offline measures also indicated that already 6- and 9-month-olds formed expectations about a target object's size based on the observed grasp aperture of a human hand (e.g., Daum, Vuori, Prinz, & Aschersleben, 2009), with positive correlations to infants' ability to perform whole-hand and precision grasps (e.g., Loucks & Sommerville, 2012, 2018). Thus, infants' emerging ability for forward modeling seems to support goal prediction in both action execution and action observation.

Ambrosini et al. (2011, 2013) also presented a reaching closed fist together with the small and large target object. Here, when information about grasp aperture was not available, only adults, but not the 6-, 8-, and 10-month-olds, performed predictive gaze-shifts, and the adults' predictive gaze-shifts were faster toward the large than small target object. It is questionable whether infants' tracking gaze was due to the lack of pre-shaping information or to the unfamiliarity of the closed-fist reaching action. But when a hand performed a familiar reaching action toward only one target object with a constant medium grasp aperture, 12-month-olds performed predictive gaze-shifts when the object was large, but showed tracking gaze when the object was small (Henrichs, Elsner, Elsner, & Gredebäck, 2012). For familiar actions where information about hand pre-shaping was not available, the size of the target object thus influenced goal prediction in 12-month-olds and adults.

The idea of a link between forward modeling and earlier or faster predictive gaze-shifts toward large than small target objects is also supported by similar effects of target-size in infants' active reaching. Seven-, 9-, and 11-month-olds showed a longer phase of slow movement at the end of reaches for small than large target objects, indicating that infants needed visual feedback to precisely place their fingers around a small object (Zaal & Thelen, 2005). Likewise, adults rely more on feedback-control for actions toward small targets, resulting in slow movement but ensuring higher accuracy, but on feedforward processes for fast actions toward large targets (e.g., Seidler, Noll, & Thiers, 2004). A relation between goal-predictive gaze-shifts and feedforward models was also found in 6-month-olds (Gredebäck et al., 2018). Further, the 12-month-olds in Henrichs et al. (2012) generated predictive gaze-shifts for the large-object reaches already after the first trials, suggesting a rapid shift from feedback to feedforward processes. By contrast, gaze for the small-object reaches remained reactive across trials, probably because infants still sampled observable information from the ongoing action.

Some authors have proposed that infants base their online goal prediction mainly on visual information about the movement, or on a mere extrapolation of the agent's trajectory (e.g., Ganglmayer et al., 2019), but this would have been possible also in the closed-fist and pre-shaped small-object conditions. We therefore take the findings of Ambrosini et al. (2013) and Henrichs et al. (2012) to indicate that the presence of a salient and unambiguous target object, together with visual features of a familiar agent and action, triggered infants' goal-predictive gaze-shifts. Under an event-prediction perspective (e.g., Baldwin, 2002; Zacks et al., 2007; see Fig. 2), the presence of salient and familiar visual features in the action event's initial state and at the beginning of the movement leads to increased activation of a stored event schema, which in turn decreases prediction uncertainty by exerting top-down influences regarding upcoming movement and goal features. A large target object enables forward modeling and thus increases the probability that infants predictively shift their gaze from the familiar moving agent toward the target object, where the subsequent action event will probably begin. This can also explain why 10-month-olds performed predictive gaze-shifts toward small target objects in Ambrosini et al. (2013), but 12-month-olds did not do so in Henrichs et al. (2012). The hand's pre-shaping, which was present in the former but not the latter study, probably added to the available visual features in the action's initial state, and therefore increased the probability that a stored event schema could be activated, enabling goal prediction via feedforward processes. As outlined below, this would fit to the assumption of an interplay of bottom-up information processing and top-down influences in infants' action-goal prediction.

6. The impact of agency cues: Self-propelledness, equifinality, salient action effects

Experience-based accounts claim that infants can predict action goals only for familiar actions and familiar (i.e., human) agents (e.g., Falck-Ytter et al., 2006). However, *cue-based accounts* suppose that certain features of the agent or its behavior are particularly important for infants' action-goal prediction (e.g., Bíró & Leslie, 2007; Gergely, Nádasdy, Csibra, & Bíró, 1995; Leslie, 1995). Human hands display such *agency cues*, like the ability for self-propelled movement through an internal energy source, allowing for autonomous starts from rest or for varying movement trajectory or speed (e.g., Baron-Cohen, 1994; Premack, 1990). Other agency cues are adaptive behavior to situational constraints by equifinal goal approaches (e.g., Bíró & Leslie, 2007; Csibra & Gergely, 1998), or producing salient action effects, which indicates goal- or intention-driven behavior (e.g., Elsner, 2007; Uithol & Paulus, 2014). According to cue-based accounts, infants can predict action goals also for unfamiliar non-human agents when these display agency cues.

Offline measures indeed yielded the looking-time pattern indicating formed action-goal expectations for non-human agents in 5- to 6-month-olds when a target-approaching box was self-propelled (Luo & Baillargeon, 2005) or when a ball adjusted its target-approaching movements to situational constraints (Gergely et al., 1995). For unfamiliar actions, 6- and 8-month-olds formed action-goal expectations when a back-of-hand toy-touching action produced a salient action effect (i.e., dislocating the target object; Jovanovic et al., 2007; Király, Jovanovic, Prinz, Aschersleben, & Gergely, 2003). In a systematic investigation, Bíró and Leslie (2007) applied Woodward's (1998) paradigm and familiarized 6-, 9-, and 12-month-olds to a human hand or a paper tube that repeatedly poked one of two target objects. Because infants execute poking from about 9 months, the observed action was unfamiliar in 6-month-olds, but it was familiar for the hand and unfamiliar for the tube in 9- and 12-month-olds. Interestingly, the display of various agency cues during familiarization influenced infants' looking times for change-of-path and change-of-goal test events with swapped target-object locations. When the agent displayed only equifinality (i.e., target-approach from different angles across trials), infants of all ages showed the looking-time pattern indicating formed action-goal expectations

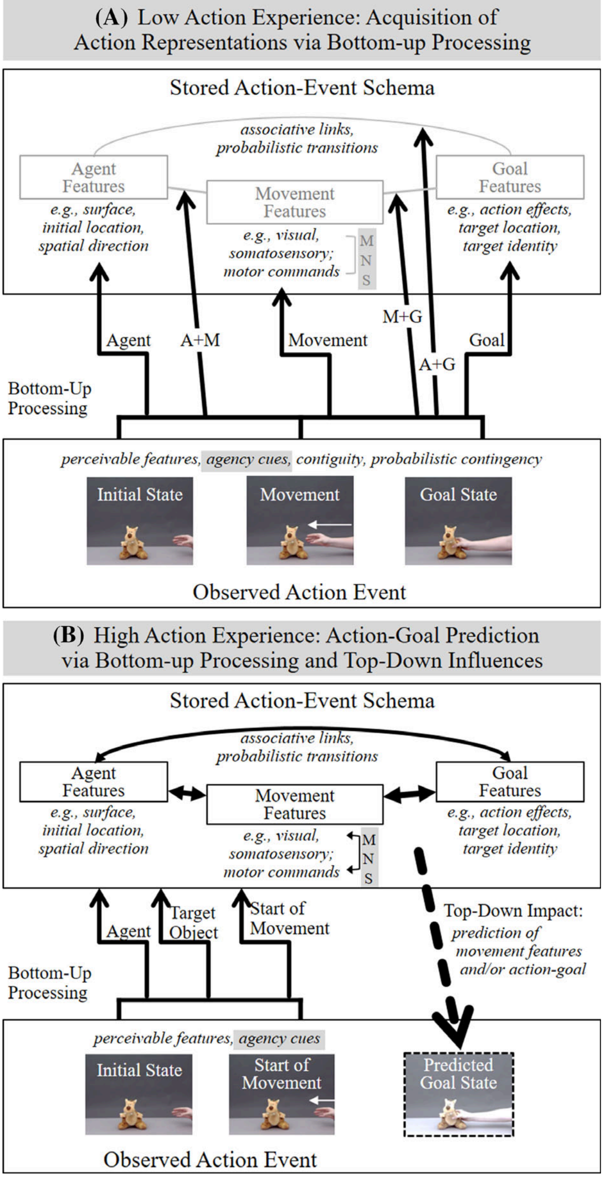

Fig. 2. Depiction of the supposed interplay between bottom-up and top-down processes during infants' action observation with either low (A) or high (B) action experience. Lines represent associative links between stored feature representations, and arrows represent directed paths on which activation can spread. Gray text and thin lines represent fragmentary feature representations and weak associations; black text and bold lines represent rich feature representations and strong associations. Activation triggered by simultaneous perception of features strengthens the respective associations between agent and movement features (A + M), movement and goal features (M + G), or agent and goal features (A + G). MNS, mirror neuron system.

for the hand, but not for the tube. Hence, the 9- and 12-month-olds formed a goal expectation and detected a (mis-)match between the observed and the expected goal state for the familiar agent and action, and the agency cue apparently helped the 6-month-olds to do so for the unfamiliar action. For the unfamiliar agent, 9- and 12-month-olds detected the goal (mis-)match when the tube displayed self-propelled movement and produced a salient action effect (i.e., lifting up the object), and the 6-month-olds also did so, but needed to see all three agency cues.

To explain how agency cues support infants' forming of goal expectations, cue-based accounts propose that first, humans are innately equipped with cognitive modules that are sensitive to these cues, especially to self-propelledness (e.g., Baron-Cohen, 1994; Carey, 2009; Leslie, 1995; Premack, 1990). Second, agency cues help to identify the to-be-attained goal of an observed action (e.g., Gergely & Csibra, 2003; Southgate, 2013). Based on an analysis of physical and semantic action properties (including agency cues and underlying intentions), top-down emulation outside of the motor system allows for goal identification, independently of the agent's familiarity (Csibra, 2007; Jacob, 2008; Prinz, 2006). Once the action goal has been identified, the observer's motor system becomes activated in order to predict how this goal will most likely be achieved, which then enables goal-predictive behavior (Csibra, 2007; Elsner, 2007; Southgate, 2013). In contrast, direct-matching accounts suppose that observing a familiar action directly activates the corresponding motor representation, which then enables goal prediction (e.g., Falck-Ytter et al., 2006). However, EEG studies have revealed motor-system activation when 9-month-olds observed a mechanical claw reaching for an object (Southgate & Begus, 2013) and when 8-month-olds observed a walking movement they could not yet perform (de Klerk, Southgate, & Csibra, 2016), which supports the cue-based accounts' assumption that motor-system activation is possible without direct matching.

A final notion of cue-based accounts is that infants need to see agency cues as long as they have only little experience with an action. However, with growing experience, frequently occurring agency cues become linked to the perceivable features of the agent or action, until eventually, the agency cues become redundant for goal prediction (Bíró & Leslie, 2007; Southgate, 2013). Whereas experience-based accounts highlight that infants need first-person experience with a specific action to form a corresponding motor representation that is activated during action observation (e.g., Falck-Ytter et al., 2006; Rizzolatti et al., 2001; Woodward, 1998, 1999), cue-based accounts claim that the co-occurrence of an agent and agency cues can be perceived in self-performed or observed actions. Because infants have more active and observational experience with human actions, which display agency cues, online goal prediction starts at an earlier age for hands than mechanical claws, even in situations where hands do not display agency cues (e.g., Adam et al., 2016; Cannon & Woodward, 2012; Kanakogi & Itakura, 2011). Offline measures provided first evidence for an interplay between action experience and the necessity of agency cues. Here, 12-month-olds showed the looking-time pattern indicating formed goal expectations for an unfamiliar back-of-hand toy-touching action that did not produce a salient action effect, but only when infants had previously experienced (actively and by observation) this action together with a salient action effect (i.e., lifting-up the toy; Bíró, Verschoor, Coalter, & Leslie, 2014). In contrast, 9-month-olds did not benefit from the prior experience, indicating that they could not integrate the observed agency cue into their still weak experience of toy-touching.

Evidence for infants' online action-goal prediction for non-human agents that show agency cues is still sparse and mixed. In Falck-Ytter et al. (2006), 6- and 12-month-olds did not show predictive gaze-shifts when observing a self-propelled ball with human-like features (i.e., a face, legs, and arms) that moved independently toward a bucket and produced a salient action effect (i.e., sound and moving smiley face at the bucket). Further, for a self-propelled non-human agent that temporarily disappeared under an occluder on its path to one of two potential target objects, 9- and 24-month-olds showed predictive gaze-shifts, but only to the location of the agent's re-appearance (Daum et al., 2012). This indicates that infants' prediction was based on the movement's trajectory rather than on the target object's identity (see also Ganglmayer et al., 2019; Paulus et al., 2011). Predictive gaze-shifts to the previous target object, indicating flexible goal-based predictions, occurred only at 36 months. However, 13-month-olds showed predictive gaze-shifts for a simpler action where a ball that displayed self-propelled target-directed movement (i.e., jump over an obstacle to reach another ball) and equifinality (i.e., adjust jump to varying obstacle-height; Bíró, 2013).

Our own research aimed at clarifying which agency cues or cue combinations are crucial for infants' goal-predictive gaze-shifts when observing actions of human or mechanical agents. As reported above, we found predictive gaze-shifts in 11-month-olds for toy-grasping actions of a human hand, but tracking gaze for a mechanical claw (Adam et al., 2016). However, when the toy-grasping claw displayed the three agency cues of self-propelled movement, equifinality, and action-effect production, 11-month-olds generated predictive gaze-shifts (Adam, Reitenbach, & Elsner, 2017), fitting Bíró and Leslie's (2007) findings with offline measures. Additionally, as for the grasping human hand (Adam et al., 2016), infants' gaze-arrival times increased across the first trials when the claw displayed agency cues, indicating a rapid shift from feedback to feedforward processes (see Henrichs et al., 2012). Adults showed predictive gaze-shifts for the mechanical agent irrespective of agency cues, probably due to their rich experience with own and observed object grasping and tool use.

To form a goal expectation for the non-human agent, 6-month-olds in Bíró and Leslie (2007) needed to see more agency cues than 9- or 12-month-olds. However, it is unclear whether just the quantity, or rather the kind or quality of agency cues is crucial for infants' goal prediction. Regarding Prinz's (1997) definition of an action, self-propelledness or equifinality characterize the movement component, and these agency cues are supposedly processed by innate cognitive modules (e.g., Baron-Cohen, 1994; Leslie, 1995; Premack, 1990). In contrast, action-effect production signifies the goal component, which several theories render as important for adults' and infants' planning, control, and perception of actions (e.g., Elsner, 2007; Elsner & Hommel, 2001; Eshuis, Coventry, & Vulchanova, 2009; Hommel et al., 2001; Paulus, 2014). In Adam and Elsner (2018), 11-month-olds showed predictive gaze-shifts when a grasping claw showed mechanical movement and action-effect production (i.e., lifting-up the target object), but tracking gaze for only self-propelled movement and equifinality without an action-effect. Only in the action-effect condition, mean gaze-arrival times increased across the first trials, indicating the shift to feedforward processes. Thus, observing the goal-related agency cue of action-effect production during the first trials, but not observing only the movement-related cues of self-propelledness and equifinality, seemed to enable 11-month-olds' online goal prediction in the subsequent trials.

To investigate the cue-based accounts' assumption that visible agency cues become redundant with growing action experience (e.g., Bíró & Leslie, 2007; Bíró et al., 2014; Southgate, 2013), we presented infants of different ages with repetitions of a toy-grasping action of a human hand, either with or without action-effect production (M. Adam & B. Elsner, unpublished data). Here, 6-month-olds, who had only recently accomplished the developmental milestone of visually guided grasping, showed tracking gaze in both conditions. Somewhat more experienced graspers at 7 months performed predictive gaze-shifts in the action-effect condition, but tracking gaze in the no-action-effect condition. Experienced graspers at 11 months did not need to see the agency cue together with the human grasping action; they generated predictive gaze-shifts in both conditions. Although these age differences require further investigation, they indicate that infants need to see more visual information during the first observations of a goal-directed action in order to be able to generate a goal-predictive gaze-shift from observing the initial state and the beginning movement as long as their action experience (and probably their stored action-event schema) is still weak (Bíró & Leslie, 2007; Southgate, 2013).

7. Integrating the impact of experience and agency cues from an action-event perspective

The research reported here demonstrates that infants perform predictive gaze-shifts toward the goals of familiar actions and for familiar human agents at an earlier age than for unfamiliar actions or agents (e.g., Adam et al., 2016; Cannon, & Woodward, 2012; Falck-Ytter et al., 2006; Kanakogi & Itakura, 2011). Regarding the underlying cognitive processes, experience-based accounts suppose that online goal prediction is enabled when observing a familiar action either directly activates the corresponding motor representation via the MNS (e.g., Falck-Ytter et al., 2006; Gredebäck & Falck-Ytter, 2015) or allows for inferring the action's goal-structure based on active action experience (Cannon & Woodward, 2012). In contrast, cue-based accounts assume that goal prediction is enabled when an agent displays agency cues, which activates innate cognitive modules for agency detection (e.g., Bíró & Leslie, 2007) and/or supports identification of the action goal and the emulation of a movement that had produced this action effect (Csibra, 2007; Southgate, 2013). Our own research shows that agency cues (in particular, producing a salient action effect) support infants' goal-predictive gaze-shifts for unfamiliar mechanical agents that perform familiar actions (Adam & Elsner, 2018; Adam et al., 2017; see also Bíró, 2013), and that visible agency cues become less important with increasing action experience (M. Adam & B. Elsner, unpublished data; see also Bíró & Leslie, 2007).

We propose that the impact of action experience and agency cues can be integrated if we conceive of actions as events (e.g., Zacks et al., 2007) that are cognitively stored as feature bundles (Hommel et al., 2001). Our approach extends the assumption of higher task demands of online goal prediction relative to offline goal evaluation (Gredebäck & Daum, 2016) by proposing an interplay of bottom-up and top-down processes that enables infants to disengage their gaze from the moving agent and to perform a predictive gaze-shift (Fig. 2). We assume that, first, infants need to process the perceivable (yet incomplete) information about the initial state and the beginning of the movement (bottom-up processing). Second, this bottom-up information needs to be mapped to semantic action-event schemata (Butz, 2016; Zacks et al., 2007) or cognitive action representations (Elsner & Hommel, 2001), which encode previously encountered features of agents, movements, and goals as well as information about temporal contiguity and probabilistic contingencies of certain features. Acquisition of action-event schemata starts as soon as motor and sensory development allow for movement execution and repeated encoding of perceivable and co-occurring action features (Elsner, 2007; Paulus, 2014). Here, the MNS constitutes a component of the action-event schema that enables direct matching of frequently co-occurring visual and somatosensory movement features and corresponding motor commands (e.g., Falck-Ytter et al., 2006; Gredebäck & Falck-Ytter, 2015). Third, with sufficient experience, action observation activates the stored action features and transitional probabilities, which can trigger forward modeling of the to-be-expected goal state (Ambrosini et al., 2011, 2013; Seidler et al., 2004), enabling predictive gaze-shifts via top-down influences (Csibra, 2007; Southgate, 2013).

Under this perspective, agency cues influence bottom-up processing by adding to the perceivable action features, in particular when experience with the observed action is low (Fig. 2A). In contrast, action experience adds to the top-down influences, determining which action features and transitional probabilities are already stored in action-event schemata. This also explains the close relations between infants' motor development and their ability for action-goal prediction (Cannon et al., 2012; Gredebäck & Melinder, 2010; Melzer et al., 2012; Sommerville et al., 2005). When an infant observes a familiar action (e.g., human toy-reaching; Fig. 2B), bottom-up processing of the features of the initial state and the beginning movement exerts sufficient activation on the acquired action-event schema, allowing for forward modeling of upcoming movement features and the to-be-achieved goal state based on stored probabilistic feature transitions. Thereby, top-down influences enable predictive gaze-shifts to the target object, where action effects will happen and a potentially following action event will start.

For unfamiliar agents or actions (e.g., a reaching mechanical claw or back-of-hand toy-touching), the stored action-event schema contains only fragmentary feature representations and none, or weak associations on which activation can spread (Fig. 2A). Because the probabilistic transitions between the initially perceived and the upcoming event features are still unknown, online goal prediction is not possible because of lacking top-down influences. Here, tracking or reactive gaze on the moving agent adds bottom-up information to the action-event schema, which eventually allows for goal prediction upon future observation of the same action. Apparently, observed action effects are particularly helpful for future action-goal prediction (Adam & Elsner, 2018; Elsner, 2007; Eshuis et al., 2009; Uithol & Paulus, 2014). Because infants primarily gain experience with agents that display agency cues (i.e., own or others' body limbs; Bíró, 2013; Bíró & Leslie, 2007), this perceivable information is also stored in action-event schemata, until finally, perceiving only the initial state and the agent's features allows for goal prediction (Fig. 2B). Further, when an unfamiliar agent or action displays visible agency cues, a corresponding familiar action-event schema with similar initial features may become activated (i.e., human reaching), enabling a predictive gaze-shift via top-down influences after having tracked the complete action event during the first trials.

Although construing actions as events allows for explanation of many of the current findings on the development of infants' action-goal prediction, future research is needed, for instance, on the exact role of the MNS and of direct matching (Gredebäck & Falck-Ytter, 2015; Jacob, 2008; Southgate, 2013) and/or on the specific relevance of action effects and of other agency cues or cue combinations (Adam & Elsner, 2018; Eshuis et al., 2009; Uithol & Paulus, 2014). Moreover, infants' acquisition of action experience should be examined in longitudinal observations or training studies, to investigate, for instance, the assumed priority of active experience over passive observation of others' actions (Gerson & Woodward, 2014; Sommerville et al., 2005) and to determine at which point action experience is sufficient for enabling forward modeling. Such evidence could also help to resolve the current debate on whether infants actually predict action goals (i.e., target identity) or rather movement endpoints (e.g., Ganglmayer et al., 2019).

In conclusion, both offline and online measures indicate that infants can form goal expectations or perform goal-predictive gaze shifts for familiar actions and for familiar human agents at an earlier age than for unfamiliar actions and/or mechanical agents. We propose that the impacts of action-experience and of agency cues on infants' action-goal prediction can be explained from an action-event perspective. In particular, we assume an interplay between bottom-up processing of the perceivable action features and top-down influences based on action-event schemata that store previously experienced features of the agent, movement, and goal state, as well as their transitional probabilities. Action experience drives the acquisition of action-event schemata via bottom-up processing, and adding visual information to an observed action event (e.g., agency cues or target-object salience) can enable top-down influences when action experience is still low. Further examination of the cognitive mechanisms that drive infant development of goal prediction for simple actions will enrich our understanding of humans' essential abilities to predict upcoming action events in more complex behavioral structures and to infer others' underlying action goals and intentions from their observable behavior.

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