**The impact of action effects on infants' predictive gaze shifts for a non-human grasping
action at 7-, 11-, and 18 months**

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Abstract

During the observation of goal-directed actions, infants usually predict the goal when the action and the agent are familiar, but they do not as easily predict the goal when the action or the agent are unfamiliar. Recent theoretical accounts suggest that predictive gaze behavior relies on a complex interplay between bottom-up- (e.g., agency cues) and top-down information (e.g., prior experience with the action), depending on an observer's prior knowledge about the unfolding action event. Based on these accounts, we hypothesized that during the observation of grasping actions performed by a mechanical claw, younger infants would need agency cues to show predictive gaze behavior, whereas older infants would be able to show predictive gaze behavior regardless of agency cues. Therefore, we presented 7-, 11-, and 18-month-old infants with videos of a mechanical claw that repeatedly approached and grasped a goal object and then either did or did not produce a salient action effect. The 7-month-olds were not predictive regardless of the salient action effect, the 11-month-olds were only predictive when the salient action effect was presented, and the 18-month-olds were predictive regardless of the salient action effect. These results therefore support the idea of a complex interplay between bottom-up and top-down information as a crucial factor for the production of predictive gaze behavior during the observation of goal-directed actions performed by mechanical agents.

Keywords : Infancy, Predictive gaze behavior, Eye tracking, Mechanical agents, Agency cues

1. Introduction

Humans live in a world that is filled with goal-directed actions: People grasp for objects, use tools for crafting or extend their hands towards each other to shake them. Per definition, an action is a movement that is performed by an agent in order to obtain a desired goal (Prinz, 1997). Sometimes, it can be crucial to predict the goal of the observed action in order to react accordingly and in a timely manner. In a social environment, this goal prediction is extremely important both in the context of competitive and cooperative situations, which is why its development has been studied extensively over the past decades.

Starting around 6 to 7 months of age, infants show goal-predictive gaze behavior when observing simple human grasping actions, that is, they shift their gaze to the to-be reached goal object before the agent arrives at its goal (e.g., Adam & Elsner, 2020; Ambrosini et al., 2013; Kanakogi & Itakura, 2011). A little later, at around 12 months of age, infants even predict the goals of more complex human actions, such as transporting toys into a bucket (Falck-Ytter, Gredebäck, & von Hofsten, 2006). It is often suggested that infants' goal predictive gaze behavior is closely linked to their ability to perform the observed actions (e.g., Falck-Ytter et al., 2006; Kanakogi & Itakura, 2011; Melzer, Prinz, & Daum, 2012). This is evidenced by correlations between infants' own abilities to perform certain actions and their ability to predict the goal of these actions, as well as by studies showing that infants struggle to predict the goal of actions performed by non-human agents or of actions they are not yet able to perform themselves (e.g., Adam, Reitenbach, & Elsner, 2017; Cannon & Woodward, 2012; Falck-Ytter et al., 2006; Kanakogi & Itakura, 2011). Additional support comes from looking-time research, in which infants' evaluation of the action goal was measured post hoc, that is, after the action goal was completed. For example, from 6 months on, infants attribute goals to grasping actions by human hands, but not when a hand touches a goal object with its back, which is an unfamiliar action, or to grasping actions by a mechanical claw, which is an unfamiliar agent (e.g.,

Woodward, 1998, 1999). The aim of the present study was to investigate 7-, 11-, and 18-month-old infants' predictive gaze behavior during the observation of simple grasping actions performed by an unfamiliar mechanical claw, and how the gaze behavior across age groups is impacted by how much knowledge the infants have about the observed event and whether or not the mechanical claw produces a salient action effect.

Recent research suggests that infants are able to predict the goal of actions by non-human agents, as long as these agents display certain behavioral agency cues, such as self-propelled movement, equifinality of goal achievement, or the ability to produce salient action effects (e.g., Adam & Elsner, 2018; Bíró, 2013). For example, Adam and Elsner (2018) presented 11-month-olds with videos of a mechanical claw approaching a toy on a linear path. Remarkably, infants showed goal-predictive gaze shifts both when the claw showed all three agency cues, and when the claw just grasped the toy and lifted it up, therefore displaying only one agency cue, that is, producing a salient action effect. This suggests that the action effect was especially important for the infants to predict the agent's goal (see Bíró, Verschoor, Coalter, & Leslie, 2014, for similar findings regarding the importance of action effects). In another condition, the claw just grasped the toy and then froze in place. In this case, infants showed tracking gaze behavior, that is, they looked at the claw until it reached the goal. These results are in line with ideomotor accounts proposing that actions are primarily represented by the effects they elicit, which highlights the crucial role action effects play for infants' ability to predict the goal of an observed action event (e.g., Elsner & Hommel, 2001, Prinz, 1997).

Gumbsch, Adam, Elsner, and Butz (2021) developed a generative, event-predictive computational model that successfully modeled the development of infants' gaze behavior when observing human and non-human agents performing goal-directed actions. The Cognitive Action Prediction Model in Infants (CAPRI) proposes that infants generate internal probabilistic generative models of observed action events and transitions between events. These

internal models are suggested to develop through infants' sensorimotor interaction with the environment (e.g., when infants repeatedly grasp for and interact with objects or observe others doing so). During action generation and observation, CAPRI suggests that gaze behavior is inferred and optimized by means of active inference based on the Free Energy Principle (Friston, 2010; Friston et al., 2015), thus striving to minimize anticipated uncertainty. As a result, predictive gaze behavior developed when the model was trained on object interaction events. With hardly any knowledge about grasping actions, the model tracked the moving hand to minimize uncertainty and to gain information about its future position. Later during training, predictive gaze shifts are generated progressively more consistently because CAPRI attempts to minimize the uncertainty about whether, when, and how the hand is going to grasp the target object (Gumbsch et al., 2021).

Similarly, Elsner and Adam (2020) argued that actions can be seen as events that are cognitively stored as feature bundles (Hommel, Müsseler, Aschersleben, & Prinz, 2001; Zacks, Speer, Swallow, Braver, & Reynolds, 2007). Via an interaction between bottom-up and top-down processes, infants' generation of predictive gaze behavior is suggested to be based on three steps. First, bottom-up features of the ongoing, yet incomplete, action have to be perceived and processed. These features include for example the agent's appearance or the kinematics of the movement towards the goal. Second, this bottom-up information is mapped to stored action-event schemata or cognitive action representations (Elsner & Hommel, 2001; Butz, 2016; Zacks et al., 2007). Such representations encode acquired action experience, in the form of feature nodes connected by associations of various strength. The number of features and the associative strength increases upon each performance or observation of an action. For example, action-event schemata represent that when a hand moves towards an object, this is usually followed by a salient action effect. Third, when sufficient action experience is available, the perception of bottom-up information about the agent, potential goal object, and start of the movement

triggers predictive gaze behavior via top-down processes, anticipating the expected goal state of that action (Csibra, 2007; Elsner & Adam, 2020; Southgate, 2013).

Therefore, as long as infants have only little to no experience with an observed action or agent, they should not be able to predict the action goal. Instead, tracking of the unfolding bottom-up information helps infants to understand the ongoing action, thereby strengthening the stored action-event schema. Infants normally gather experience about agents that display various agency cues (e.g., Bíró, 2013; Bíró & Leslie, 2007), and this perceivable bottom-up information is then stored in action-event schemata, until the mere perception of the agent's features or the initial state of the action event is sufficient to activate the action-event schema and allows for successful goal prediction (e.g., Elsner & Adam, 2020). Following this idea, when unfamiliar agents such as mechanical claws display one or more agency cues, corresponding event schemata (linked to the agency cue) might become activated and allow for predictive gaze behavior via top-down influences in subsequent trials even for the unfamiliar agent.

This is in line with looking-time research showing that infants at 6 months need to see more agency cues than older infants at 9 or 12 months in order to attribute a goal to the action of a mechanical claw (Bíró & Leslie, 2007). Moreover, when 9-month-olds were presented with a situation that suggested that a mechanical claw was about to act goal-directedly, infants' EEG response showed patterns of goal identification (Southgate & Begus, 2013). Finally, in eye-tracking studies, adults showed goal-predictive gaze-shifts for unusual hand actions or for grasping by a mechanical claw even in the absence of any additional agency cues (Adam, Reitenbach, & Elsner, 2017; Kanakogi & Itakura, 2011). Taken together, these results illustrate how observers with limited knowledge about the observed action rely on the unfolding bottom-up information, whereas observers with more knowledge can rely on their stored top-down

information that they have gathered through prior knowledge or experience with an action event or an agent.

A recent study investigated infants' use of bottom-up- versus top-down information across the first year of life, by repeatedly presenting 6-, 7-, and 11-month-olds with a hand that approached and grasped a goal object, followed either by a salient action effect (e.g., lifting up the object, accompanied by a sound) or by just freezing in place (Adam & Elsner, 2020). At 6 months, infants showed tracking gaze behavior regardless of the salient action effect, confirming the assumed behavior of infants who have just recently accomplished the motor-development milestone of visually-guided grasping. In contrast, at 11 months, when infants are experienced in grasping, predictive gaze behavior occurred in both conditions. Interestingly, at 7 months, infants were predictive in the human-hand condition only with the salient action effect, and 7-month-olds did not show predictive gaze behavior when a grasping mechanical claw produced the salient action effect. These results might reflect infants' still weak representations for human grasping actions, and these representations were only able to be activated via additional agency cues when infants observed a human hand. For the claw, however, there were not yet representations that could be activated, and therefore, the agency cue did not lead to predictive gaze behavior.

The current study aimed to investigate this interplay of top-down and bottom-up information in the context of predictive gaze behavior in more detail. If indeed observers, depending on their knowledge about an observed action, rely on either prior top-down knowledge about the observed action or on presented bottom-up information when generating predictive eye-movements, we should see similar developmental patterns, albeit at different ages, for familiar agents and for unfamiliar agents. For example, compared to human hands, infants have much less conceptual knowledge about claws, how mechanical claws are able to grasp and manipulate objects, and how claws can be used as tools. Therefore, we predicted that the results by Adam

and Elsner (2020) across different age groups could be replicated with an unfamiliar agent such as a mechanical claw, when the infants that are tested are older and have more experience with grasping in general, but also with the use of tools to obtain a desired means (e.g., McCarty, Clifton, & Collard, 2001). If a similar impact of salient action effects on predictive gaze behavior as in human hands could be found for a mechanical claw, this would provide further evidence for the interplay of top-down and bottom-up information. Additionally, this idea implies that there should be an age at which infants possess sufficient action knowledge and would predict the goal of a mechanical claw even without any additional agency cues. To our knowledge, this would be the first study to show that infants predict the goal of an action performed by a mechanical in the absence of any additional agency cues during ongoing and complete action presentations.

Therefore, we repeatedly presented 7-, 11-, and 18-month-olds with a video in which a mechanical claw approached and grasped a goal object and then either did or did not produce a salient action effect. During these presentations, we recorded infants' eye movements to investigate first, at which age infants use the agency cue to predict the goal of a simple grasping action performed by a mechanical claw. Second, we investigated whether there would be a learning process that manifests itself as faster gaze shifts to the goal across trials. The three age groups were chosen based on prior research: We expected the 7-month-olds to show tracking gaze behavior regardless of the salient action effect based on 7-month-olds' limited knowledge about both grasping actions and tool-use actions and research reporting that 7-month-olds do not predict the goal of a mechanical claw even when it produces salient action effects (Adam & Elsner, 2020; McCarty et al., 2001). We expected the 11-month-olds to be predictive in the condition with the action effect, but to show tracking gaze behavior in the condition without the action effect, because they have more knowledge about grasping actions than the 7-month-olds and showed predictive gaze behavior when a mechanical claw performed salient action

effects, but still have relatively limited experience with tool-use actions and have been reported to track a mechanical claw reactively in the absence of additional agency cues (Adam & Elsner, 2018; McCarty et al., 2001). Finally, we expected the 18-month-olds to be predictive regardless of the action effect, because at 18 months, the infants should already have sufficient knowledge about grasping actions and tool use. Specifically, between 14 and 19 months, infants start to engage in successful actions with claw-like tools to obtain distant objects (McCarty et al., 2001). Therefore, at 18 months, the experience with these kinds of actions should enable goal-prediction via top-down processes upon perceiving the start of the claw's grasping, even without agency cues.

2. Materials and Methods

2.1 Participants

The final sample consisted of forty-two 7-month-olds ($M = 6.9$, $SD = 0.3$, range = 6.5-7.5 months, 20 girls), forty-one 11-month-olds ($M = 10.9$, $SD = 0.3$, range = 10.5-11.5 months, 21 girls) and forty-one 18-month-olds ($M = 18.0$, $SD = 0.3$, range = 17.5-18.6 months, 22 girls). An additional 9, 8, and 4 participants, respectively, were tested but had to be excluded because they did not contribute enough valid data (criteria see below). The participants were randomly assigned to either the action effect condition (7-month-olds: $n = 21$; 11-month-olds: $n = 20$; 18-month-olds: $n = 19$) or the no-action effect condition (7-month-olds: $n = 21$; 11-month-olds: $n = 21$; 18-month-olds: $n = 22$). The parents and their children were recruited from a database where parents can sign up their child to participate in studies in the babylab. Participants mostly came from middle-class families in a small German city. During their stay at the lab, parents signed informed consent, and received 7.50 € as well as a certificate with a photograph of their child as reimbursement. This study was approved by the ethics committee of the University.

2.2 Stimuli, Apparatus, and Procedure

Participants were presented with 12 repetitions of a video showing how a claw approached and interacted with a toy. In both experimental conditions, the first part of the video was identical: The videos showed the surface of a gray table filmed from the side in front of a grey background with a toy sitting on the table at screen centre (see Figure 1). After approximately 1000 ms, a claw that was painted with a light color entered the scene from the right side of the screen and approached the toy on a linear path and grasped it (duration approx. 2140 ms). In the action effect condition, the claw then lifted the toy up, accompanied by a sound, and put the toy back on the table (duration approx. 2000 ms). Then, the screen froze and the scene was presented for another 3870 ms until the video ended. In the no action effect condition, immediately after the claw grasped the toy, the screen froze for approximately 5870 ms until the video ended. Thus, both videos were identical in length and had a total running time of about 9010 ms. Attention getter videos (e.g., a bouncing ball or a waving hand) were presented in between stimulus videos in order to redirect the participants' gaze to the screen.

Figure 1. Still frames of the stimulus videos in the action effect condition (upper row) and the no action effect condition (lower row). The two squares in the first picture depict the Areas of Interest used for data analysis. The squares were not visible during the experiment.

Gaze behavior was recorded with an SMI RED 250 mobile eye tracker mounted to a 22-inch screen. The sampling rate was 250 Hz, and the screen resolution was 1680 by 1050 pixels. During the experiment, participants sat on their caregiver's laps in front of the screen, approximately 60 cm away from the eye tracker. Caregivers had no prior knowledge about the contents of the stimuli or the purpose of the study and were instructed to only interact with their child in case she needed soothing. The experiment started with a 5-point-calibration and with manual point acceptance. The calibration stimulus was an animated picture of a pulsating circle in front of a gray background. After successful calibration, the experiment started with a total runtime of about 2.5 minutes.

2.3 Data Handling

In both conditions, we used the same Areas of Interest (AOIs) to analyze participants' gaze behavior (see Adam et al., 2016; Falck-Ytter et al., 2006; Kanakogi & Itakura, 2011, for similar criteria): a static AOI for the goal object and a moving AOI for the claw. Gaze-arrival times were calculated by subtracting the time when participants first fixated the goal AOI from the time when the claw entered the goal AOI. Gaze-arrival times above the value of 0 ms were considered predictive, gaze-arrival times around 0 ms were considered as tracking, and gaze-arrival times below 0 ms were considered reactive. A trial was valid when participants first fixated the claw AOI for at least 200 ms before they fixated the goal AOI. Additionally, values of -1000 ms or below were classified as invalid. The first trial was excluded from our analyses, because the experimental manipulation of the action effect only occurred at the end of the first video. Participants needed to have at least two valid trials among the analyzed trials 2-12 to be included in our analyses, a criterion that has been used in studies with infants around 6 months of age (Adam & Elsner, 2020; Gredebäck, Lindskog, Juvrud, Green, & Marciszko, 2018; Kanakogi & Itakura, 2011). The gaze-arrival times in the valid trials were then averaged for every participant to create a mean gaze-arrival time. On average, the 7-month-olds contributed

significantly more trials in the action effect condition ($n = 7.8$, $SD = 3.4$) than in the no action effect condition ($n = 5.1$, $SD = 2.6$), $t(40) = -2.92$, $p < .01$, $r = .4$. Both the 11-month-olds (action effect condition: $n = 8.4$, $SD = 3.1$; no action effect condition: $n = 8.2$, $SD = 2.6$; $t(39) = -0.23$, $p = .82$, $r = .04$) and the 18-month-olds (action effect condition: $n = 9.2$, $SD = 2.1$; no action effect condition: $n = 9.4$, $SD = 2.1$; $t(39) = 0.31$, $p = .76$, $r = .05$) contributed a similar number of valid trials in both conditions. In neither age group, there was a significant correlation between the number of valid trials and the mean gaze-arrival time, all $ps > .28$.

To test our hypotheses, we conducted ANOVAs and Bonferroni-corrected independent samples t -tests in order to compare the mean gaze-arrival times as a function of the between-subjects factors age group and condition. We also performed one-sample t -tests against the threshold of 0 ms for every subgroup to classify the gaze behavior as predictive, tracking, or reactive. In case of a null result, we also included BF_{01} , indicating the Bayes Factor in favor of the H_0 over H_1 . Additionally, we used linear and curvilinear regression analyses with linear, logarithmic, and quadratic curve fitting in every subgroup to investigate potential changes of the mean gaze-arrival times across trials 2 to 12.

3. Results

The ANOVA on mean gaze-arrival time with age group (7 months vs. 11 months vs. 18 months) and condition (action effect vs. no action effect) as between-subjects factors yielded a significant main effect of age group, $F(2,118) = 17.0$, $p < .001$, $\eta^2 = .22$, a significant main effect of condition, $F(1,118) = 13.5$, $p < .001$, $\eta^2 = .10$, and a significant interaction between age group and condition, $F(2,118) = 3.2$, $p < .05$, $\eta^2 = .05$ (see Figure 2). Regarding the main effect of the age group, post-hoc independent-samples t -tests (Bonferroni corrected with $\alpha = .016$) revealed that both the 11-month-olds, $t(81) = -3.83$, $p < .001$, $r = .4$, and the 18-month-olds, $t(81) = -5.16$, $p < .001$, $r = .5$, had significantly faster mean gaze-arrival times than the 7-month-olds. There was, however, no significant difference between the 11- and the 18-month-

olds, $t(80) = -1.36, p = .18, r = .2$. The main effect of condition resulted from faster mean gaze-arrival times in the action effect than no action effect condition. To explore the significant interaction, we compared the mean gaze-arrival times between conditions for each group separately by independent-samples t -tests (Bonferroni corrected with $\alpha = .016$). Significantly faster mean gaze-arrival times in the action effect than no action effect condition occurred in both the 7-month-olds, $t(40) = -3.65, p < .001, r = .5$, and the 11-month-olds, $t(39) = -2.74, p < .01, r = .4$, but for the 18-month-olds, there was no significant condition difference, $t(39) = -0.12, p = .91, r = .02$.

Regarding the one-sample t -tests against the threshold of 0 ms, as expected, the 7-month-olds were reactive in the no action effect condition, $t(20) = -5.74, p < .001, r = .8$, and were tracking in the action effect condition, $t(20) = -0.05, p = .96, r = .01, BF_{01} = 6$. The 11-month-olds were tracking in the no action effect condition, $t(20) = -0.37, p = .72, r = .08, BF_{01} = 5.6$, and predictive in the action effect condition $t(19) = 2.96, p < .01, r = .6$. Finally, the 18-month-olds were predictive in both the no action effect condition, $t(21) = 2.9, p < .01, r = .5$, and the action effect condition, $t(18) = 2.8, p < .05, r = .6$.

Figure 2. Mean gaze-arrival times for the 7-, 11-, and 18-month-olds in the action effect and the no action effect condition. Positive and negative values represent mean gaze-arrival times before and after the claw arrived at the goal AOI. Error bars represent standard-errors, and the asterisks mark mean gaze-arrival times significantly different from 0 ms, * = $p < .05$, ** = $p < .01$, *** = $p < .001$.

The regression analyses on mean gaze-arrival times across trials 2-12 in the action effect condition revealed a significant fit for a logarithmic function for the 7-month-olds ($y = 137.25\ln(x) - 241.55$, $R^2 \text{ adj} = .44$, $F(1,9) = 8.97$, $p < .05$) and a significant fit for a quadratic function for the 11-month-olds ($y = 227.96 + 179.37x - 11.98x^2$, $R^2 \text{ adj} = .66$, $F(2,8) = 10.85$, $p < .01$). In all other conditions and age groups, the analyses were not significant, all $ps > .06$ (see Figure 3). These results indicate that in the action effect condition, the mean gaze-arrival times of the 7-month-olds got rapidly faster across the first trials, albeit still with mean gaze-arrival times below or at 0 ms, and the mean gaze-arrival times of the 11-month-olds got faster across

the first half of the trials, but then slightly decelerated towards the end, always staying above 0 ms. The 18-month-olds' gaze-arrival times generally stayed in the predictive value range above 0 ms across trials in both conditions.

Figure 3. Mean gaze-arrival times across trials 2-12 for the 7-, 11-, and 18-month-olds in the action effect and no action effect condition. Positive and negative values represent mean gaze-arrival times before and after the claw arrived at the goal AOI. The curves represent the significant fit for the regression functions with most explained variance.

4. Discussion

The aim of the present study was to investigate the impact of the agency cue of producing a salient action effect on 7-, 11-, and 18-month-olds' goal-predictive gaze shifts during the observation of a non-human grasping action performed by a mechanical claw. Based on the

assumption of an interplay between bottom-up and top-down information, and prior research on the impact of salient action effects during the observation of human grasping actions (e.g., Elsner & Adam, 2020), we expected that the youngest age group would not be predictive regardless of the agency cues, that the medium age group would be predictive only when the salient action effect was presented, and that the oldest age group would be predictive regardless of the salient action effect. Indeed, we found no predictive gaze behavior regardless of the salient action effect in the 7-month-olds, predictive gaze behavior when the salient action effect was presented, but tracking gaze behavior when the salient action effect was not presented in the 11-month-olds, and predictive gaze behavior regardless of the salient action effect in the 18-month-olds. This result pattern replicates previous findings in the context of human actions for mechanical actions and shows how these patterns show up later for mechanical compared to human actions, which fits the slightly later occurring developmental milestone of tool use compared to grasping (Adam & Elsner, 2020).

First, our findings from the 7-month-olds replicate prior research showing that even in the presence of a salient action effect, infants at this age are not able to use this information in order to predict the goal of the mechanical claw (Adam & Elsner, 2020). Additionally, the present study expands these findings by showing that although infants' gaze behavior on average was not predictive in the action effect condition, mean gaze-arrival times in this condition were still significantly faster compared to the no action effect condition, with tracking gaze behavior in the action effect condition, and reactive gaze behavior in the no action effect condition. This shows that the agency cue had an impact on the 7-month-olds' gaze behavior, but that ultimately, they still did not manage to arrive with their gaze at the goal object ahead of time. Regression analyses revealed that the 7-month-olds in the action effect condition showed rapidly increasing mean gaze-arrival time across the first trials. Therefore, the 7-month-olds' gaze behavior illustrates how across trials the infants indeed used the bottom-up information in

form of the action effect to produce faster gaze shifts towards the end of the experiment. This result seems to indicate that observing the action effect might have triggered the 7-month-olds' (still weak) action knowledge to a certain degree. Compared to the results reported for 6- and 7-month-olds when observing a human hand (Adam & Elsner, 2020), the gaze behavior found in 7-month-olds in the present study is more comparable to the gaze behavior found in the younger 6-month-olds, and in the no action effect condition, the 7-month-olds even had much lower mean gaze-arrival times than the 6-month-olds. These results fit the idea that due to the later developing developmental milestone of tool-use compared to grasping (e.g., McCarty et al., 2001), the internal models for mechanical claws also develop later than the internal models for human hands. Therefore, based on the assumptions of the CAPRI model (Gumbsch et al., 2021) and Elsner and Adam (2020), we take this as evidence that the 7-month-olds in the present study did not yet have strong action-event schemata for actions performed by mechanical claws, which resulted in tracking gaze behavior, or in the case of the no action effect condition, even reactive gaze behavior, to maximize information gain and to minimize uncertainty by closely observing the agent and its movement. However, it is possible that the 7-month-olds would be able to predict the claw's action goal when more agency cues were provided, for example when the claw moved biologically or was self-propelled (e.g., Baron-Cohen, 1994; Bíró & Leslie, 2007; Premack, 1990).

Second, the findings from the medium age group replicate previous research reporting that 11-month-olds show predictive gaze behavior when a mechanical claw displays agency cues such as production of a salient action effect (Adam et al., 2017; Adam & Elsner, 2018). Additionally, regression analyses revealed that the 11-month-olds showed increasing mean gaze-arrival times across the first half of the experiment, and decreasing, though still predictive, mean gaze-arrival times across the second half in the action effect condition. These results show how across the first half of the experiment the observation of the action effect enabled predictive

gaze shifts. In the no action effect condition, infants' gaze followed the claw to the goal. This result is partly in line with our expectations, because it shows how seeing the action effect was able to trigger 11-month-olds' action knowledge, at least in the first half of trials. Furthermore, these mean gaze-arrival times from the 11-month-olds are strikingly similar to the ones found by Adam and Elsner (2020) at 7 months of age in the context of actions performed by human hands. This further indicates that, when stored action-event schemata are still relatively weak, infants can benefit from the display of agency cues, because they exert stronger activation of the stored action-event schemata. This activation, in turn, may enable goal prediction for subsequent observations of this action event via forward modeling and top-down processes (Csibra, 2007; Elsner & Adam, 2020; Gumbsch et al., 2021; Southgate, 2013).

Third, the findings from the 18-month-olds revealed that at this age, the infants were able to predict the goal of the ongoing action of the mechanical claw regardless of the salient action effect. To our knowledge, this is the first study to show that infants from 18 months on are able to predict the goal of a non-human agent in the absence of any additional bottom-up information. Additionally, regression analyses revealed no systematic change of gaze behavior across trials, because the 18-month-olds already started out with positive mean gaze-arrival times in the first trials. These results indicate that 18-month-olds had already built up strong internal models and strong action-event schemata with regard to grasping and tool-use actions, which they could use as top-down information during the initial observation of the claw, the potential goal object, and the start of the goal approach. At 18 months of age, infants are already quite apt at simple tool-use actions to retrieve a distant object (starting around 14 months of age; McCarty et al., 2001). Based on this, it is possible that we would find similar results already at an earlier age. However, we chose this older age group based on the fact that infants' ability to produce an action does not instantly guarantee that they would also be able to predict the goal during observation of this action (e.g., Adam & Elsner, 2020; Gredebäck et al., 2018).

The results from the regression analyses of the 7- and the 11-month-olds do not match prior findings in which no learning effects were reported for 7-month-olds (Adam & Elsner, 2020) and in which 11-month-olds were reported to show rapidly faster mean gaze-arrival times across the first trials, but no decreasing mean gaze-arrival times in the second half of the experiment (Adam et al., 2017). However, because of the very limited amount of trials, it is difficult to estimate how infants' gaze behavior would have unfolded in additional trials. For example, the 7-month-olds' gaze-arrival times would probably not have progressed into the predictive value range, because a logarithmic fit implies a flattening of the curve with an increasing number of trials. Additionally, learning effects are generally reported to be unstable and seem to occur unsystematically, even when they are measured with similar stimuli (e.g., Henrichs et al., 2012). Therefore, interpretations of these findings have to be made with caution, and further systematic research on the factors driving learning effects during action observation is needed.

It needs to be noted that the present findings are ambiguous about whether infants' gaze behavior directly relied on infants' experience with or knowledge about the observed action, or on general cognitive maturation. The notion that general maturation processes play an important role seems to be supported by the fact that infants' general ability to disengage their gaze from an interesting stimulus improves across the first year of life (Elsabbagh et al., 2013). However, producing a salient action effect exerted different impact on 7- and 11-month-olds' predictive gaze behavior for a human hand and a mechanical claw (Adam & Elsner, 2020), which cannot be explained solely by general cognitive maturation processes. Training studies in which infants learn to perform novel actions could be used to disentangle these factors by investigating the impact of systematic manipulation of such learning experience on predictive gaze behavior. For example, a short training session in which infants were encouraged to actively engage in a novel action altered infants' subsequent looking times during observation of that action, indicating

changed attribution of goal-directedness (Gerson & Woodward, 2014; Sommerville, Woodward, & Needham, 2005; Woodward, 2009). However, the effect of training sessions on infants' predictive gaze behavior is still scarce.

Taken together, our results expand previous work on infants' goal-predictive gaze behavior in the context of human hands to simple actions performed by mechanical agents. Framed according to the theoretical model by Elsner and Adam (2020) and the CAPRI model (Gumbsch et al., 2021), at 7 months, infants' stored action representations are probably still too weak to enable predictive gaze behavior, even in the presence of the agency cue of producing a salient action effect (Bíró & Leslie, 2007). At 11 months of age, infants' stored action representations are still weak, but strong enough to be activated by some observations of the production of a salient action effect during the first trials, which enables goal prediction upon observing the action's start in subsequent trials. Finally, at 18 months, infants' stored action representations are strong enough to be activated already for the first action observations, even in the absence of any additional agency cues. Therefore, these results provide further evidence for the interplay between bottom-up and top-down information during the observation of goal-directed actions and illustrate how the shifted developmental courses of this behavior follow infants' motor development and acquired action experience with mechanical agents compared to human agents (Csibra, 2007; Elsner & Adam, 2020; Southgate, 2013). Future research should further investigate the specific role of infants' agentic experience with the observed action by applying training paradigms, which would shed more light on the interplay of perceptual bottom-up information and experience-based top-down processes underlying the developmental course of infants' goal-predictive gaze behavior.

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References

- Adam, M., & Elsner, B. (2018). Action effects foster 11-month-olds' prediction of action goals for a non-human agent. *Infant Behavior and Development*, 53, 49–55.
<https://doi.org/10.1016/j.infbeh.2018.09.002>
- Adam, M., & Elsner, B. (2020). The impact of salient action effects on 6-, 7-, and 11-month-olds' goal-predictive gaze shifts for a human grasping action. *PLOS ONE*, 15, e0240165. doi: 10.1371/journal.pone.0240165
- Adam, M., Reitenbach, I., & Elsner, B. (2017). Agency-cues and 11-month-olds' and adults' anticipation of action goals. *Cognitive Development*, 43, 37–48.
<https://doi.org/10.1016/j.cogdev.2017.02.008>
- Adam, M., Reitenbach, I., Papenmeier, F., Gredebäck, G., Elsner, C., & Elsner, B. (2016). Goal saliency boosts infants' action predictions for human manual actions, but not for mechanical claws. *Infant Behavior and Development*, 44, 29-37. doi: 10.1016/j.infbeh.2016.05.001
- Ambrosini, E., Reddy, V., de Looper, A., Costantini, M., Lopez, B., & Sinigaglia, C. (2013). Looking ahead: Anticipatory gaze and motor ability in infancy. *PLOS ONE*, 8, e67916. doi: 10.1371/journal.pone.0067916
- Baron-Cohen, S. (1994). How to build a baby that can read minds: Cognitive mechanisms in mind-reading. *Cahiers de Psychology Cognitive/Current Psychology of Cognition*, 13, 513-552.
- Bíró, S. (2013). The role of the efficiency of novel actions in infants' goal anticipation. *Journal of Experimental Child Psychology*, 116, 415-427. doi: 10.1016/j.jecp.2012.09.011

- Bíró, S., & Leslie, A. (2007). Infants' perception of goal-directed actions. Development through cue-based bootstrapping. *Developmental Science*, 10, 379-398. doi: 10.1111/j.1467-7687.2006.00544.x
- Bíró, S., Verschoor, S., Coalter, E., & Leslie, A. M. (2014). Outcome producing potential influences twelve-month-olds' interpretation of a novel action as goal-directed. *Infant Behavior and Development*, 37, 729-738. doi: 10.1016/j.infbeh.2014.09.004
- Butz, M. V. (2016). Towards a unified sub-symbolic computational theory of cognition. *Frontiers in Psychology*, 7, Article 925. <https://doi.org/10.3389/fpsyg.2016.00925>
- Cannon, E. N., & Woodward, A. L. (2012). Infants generate goal-based action predictions. *Developmental Science*, 15, 292-298. doi: 10.1111/j.14677687.2011.01127.x
- Csibra, G. (2007). Action mirroring and action understanding: An alternative account. *Sensorimotor Foundations of Higher Cognition*, 22, 427-451. doi: 10.1093/acprof:oso/9780199231447.003.0020
- Elsabbagh, M., Fernandes, J., Webb, S. J., Dawson, G., Charman, T., & Johnson, M. H. (2013). Disengagement of visual attention in infancy is associated with emerging autism in toddlerhood. *Biological Psychiatry*, 74, 189-194. doi: 10.1016/j.biopsych.2012.11.030
- Elsner, B., & Adam, M. (2020). Infants' goal prediction for simple action events: The role of experience and agency cues. *Topics in Cognitive Science*. doi: 10.1111/tops.12494
- Elsner, B., & Hommel, B. (2001). Effect anticipation and action control. *Journal of Experimental Psychology*, 27, 229-240. doi: 10.1037/0096-1523.27.1.229
- Falck-Ytter, T., Gredebäck, G., & von Hofsten, C. (2006). Infants predict other people's action goals. *Nature Neuroscience*, 9, 878-879. doi:10.1038/nrn1729
- Friston, K. (2010). The free-energy principle: a unified brain theory?. *Nature Reviews Neuroscience*, 11, 127-138. doi:10.1038/nrn2787.

- Friston, K., Rigoli, F., Ognibene, D., Mathys, C., Fitzgerald, T., & Pezzulo, G. (2015). Active inference and epistemic value. *Cognitive Neuroscience*, 6, 187-214. doi: 10.1080/17588928.2015.1020053.
- Gerson, S. A., & Woodward, A. L. (2014). The joint role of trained, untrained, and observed actions at the origins of goal recognition. *Infant Behavior and Development*, 37, 94-104. doi: 10.1016/j.infbeh.2013.12.013
- Gredebäck, G., Lindskog, M., Juvrud, J. C., Green, D., & Marciszko, C. (2018). Action prediction allows hypothesis testing via internal forward models at 6 months of age. *Frontiers in Psychology*, 9, 290. doi: 10.3389/fpsyg.2018.00290
- Gumbsch, C., Adam, M., Elsner, B., & Butz, M. V. (2021). Emergent goal-anticipatory gaze in infants via event-predictive learning and inference. *PsyArXiv*, Preprint doi: 10.31234/osf.io/9g8uj
- Henrichs, I., Elsner, C., Elsner, B., & Gredebäck, G. (2012). Goal salience affects infants' goal-directed gaze shifts. *Frontiers in Psychology*, 3, Article 391. doi: 10.3389/fpsyg.2012.00391
- Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding (TEC): A framework for perception and action planning. *Behavioral and Brain Sciences*, 24, 849–937. <https://doi.org/10.1017/S0140525X01000103>
- Kanakogi, Y., & Itakura, S. (2011). Developmental correspondence between action prediction and motor ability in early infancy. *Nature Communications*, 2, 341. doi: 10.1038/ncomms1342
- McCarty, M. E., Clifton, R. K., & Collard, R. R. (2001). The beginnings of tool use by infants and toddlers. *Infancy*, 2, 233-256. doi: 10.1207/S15327078IN0202_8

- Melzer, A., Prinz, W., & Daum, M. M. (2012). Production and perception of contralateral reaching: A close link by 12 months of age. *Infant Behavior and Development*, 35, 570-579. doi: 10.1016/j.infbeh.2012.05.003
- Premack, D. (1990). The infant's theory of self-propelled objects. *Cognition*, 36, 1-16. [https://doi.org/10.1016/0010-0277\(90\)90051-K](https://doi.org/10.1016/0010-0277(90)90051-K).
- Prinz, W. (1997). Perception and action planning. *European Journal of Perception and Action Planning*, 9, 129-154. <https://doi.org/10.1080/713752551>.
- Sommerville, J. A., Woodward, A. L., & Needham, A. (2005). Action experience alters 3-month-olds infants' perception of others' actions. *Cognition*, 96, B1-B11. doi: 10.1016/j.cognition.2004.07.004
- Southgate, V. (2013). Do infants provide evidence that the mirror system is involved in action understanding? *Consciousness and Cognition*, 22, 1114-1121. doi: 10.1016/j.concog.2013.04.008
- Southgate, V., & Begus, K. (2013). Motor activation during the prediction of nonexecutable actions in infants. *Psychological Science*, 24, 828-835. doi: 10.1177/0956797612459766
- Woodward, A. L. (1998). Infants selectively encode the goal object of an actor's reach. *Cognition*, 69, 1-34. doi: 10.1016/S0010-0277(98)00058-4
- Woodward, A. L. (1999). Infants' ability to distinguish between purposeful and non-purposeful behaviors. *Infant Behavior and Development*, 22, 145-160. doi: 10.1016/S0163-6383(99)00007-7
- Woodward, A. L. (2009). Infants' grasp of others' intentions. *Current Directions in Psychological Science*, 18, 53-57. doi: 10.1111/j.1467-8721.2009.01605.x

Zacks, J. M., Speer, N. K., Swallow, K. M., Braver, T. S., & Reynolds, J. R. (2007). Event perception: A mind/brain perspective. *Psychological Bulletin*, 133, 273–293.

<https://doi.org/10.1037/0033-2909.133.2.273>