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# 1 **Infants' motor proficiency and statistical learning for actions**

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11 **Keywords: statistical learning, motor development, eye-tracking, infant cognition, action**  
12 **prediction**

## 13 **Abstract**

14 Prior research has shown that infants learn statistical regularities in action sequences better than they  
15 learn non-action event sequences. This is consistent with current theories claiming that the same  
16 mechanism guides action observation and action execution. The current eye-tracking study tested the  
17 prediction, based on these theories, that infants' ability to learn statistical regularities in action  
18 sequences is modulated by their own motor abilities. Eight- to 11-month-old infants observed an  
19 action sequence containing two deterministic action pairs (i.e., action *A* always followed by action *B*)  
20 embedded within an otherwise random sequence. One pair was performed with a whole-hand grasp.  
21 The second pair was performed with a pincer grasp, a fine motor skill that emerges around 9 months  
22 of age. Infants were then categorized into groups according to which grasp was dominant in their  
23 motor repertoire. Predictive looks to correct upcoming actions during the deterministic pairs were  
24 analyzed to measure whether infants learned and anticipated the sequence regularities. [Findings](#)  
25 [indicate that infants learned the statistical regularities: across motor groups, they made more correct](#)  
26 [than incorrect predictive fixations to upcoming actions. Overall, learning was not significantly](#)  
27 [modulated by their dominant grasping abilities. However,](#) infants with a dominant pincer grasp  
28 showed an earlier increase in correct predictions for the pincer grasp pair and not the whole-hand  
29 grasp. Likewise, infants with a dominant whole-hand grasp showed an early increase in correct  
30 predictions for the pair performed with a whole-hand grasp, and not the pincer grasp. Together, these  
31 findings suggest that infants' ability to learn action sequences is facilitated when the observed action  
32 matches their own action repertoire. However, findings cannot be explained entirely by motor  
33 accounts, as infants also learned the actions less congruent with their own abilities. Findings are  
34 discussed in terms of the interplay between the motor system and additional non-motor resources  
35 during the acquisition of new motor skills in infancy.

36

37

38 **1 Introduction**

39 Within the first months of life, infants begin to demonstrate remarkable abilities to form expectations  
40 about the actions they observe others perform. Infants readily anticipate the outcomes of observed  
41 actions and the trajectories of an actor's movements as they unfold (Ambrosini et al., 2013; Falck-  
42 Ytter, Gredebäck, & von Hofsten, 2006). For instance, they can predict that an adult will bring a cup  
43 to her mouth upon grasping it, long before they themselves can grasp mugs and drink from them  
44 (Hunnius & Bekkering, 2010). The mechanisms that support this ability have recently been a focus of  
45 intense study (for a review, see Hunnius & Bekkering, 2014). This body of work has centered around  
46 understanding how infants learn to anticipate observed actions based on observational experiences  
47 and their own developing action experiences.

48 Observational experiences create opportunities for infants to learn the statistical regularities in their  
49 environment. A recent surge of empirical work has provided convincing evidence that infants can  
50 detect multiple types of statistical regularities in different sensory domains from early in life (Aslin,  
51 Saffran, & Newport, 1998; Fiser & Aslin, 2001; Kirkham, Slemmer, & Johnson, 2002; Slone &  
52 Johnson, 2015; Teinonen, Fellman, Näätänen, & Alku, 2009). For instance, at 8 months of age,  
53 infants can segment novel auditory sequences into word-like units based on the transitional  
54 probabilities between syllables (Saffran, Aslin, & Newport, 1996). They can also form visual  
55 associations between objects and spatial locations based on their recurring co-occurrence (Kirkham et  
56 al., 2002) and can anticipate where an object will appear next based on those learned associations  
57 (Marcus, Vijayan, Rao, & Vishton, 1999).

58 Recent evidence has shown that statistical learning abilities extend to the action domain as well.  
59 Human action contains inherent sequential structure within a seemingly complex stream of motion  
60 (Baldwin & Baird, 2001; Zacks, 2004). From early in life, infants are sensitive to regularities in the  
61 actions they observe. For instance, 8-month-old infants segment observed action streams into  
62 separate units similarly to how they segment auditory sequences into words (Stahl, Romberg,  
63 Roseberry, Golinkoff, & Hirsh-Pasek, 2014). Within the first year of life, infants can learn to  
64 associate actions and the effects they produce, both for actions that they observe (Paulus, Hunnius,  
65 Elk, Van Elk, & Bekkering, 2012) and those that perform themselves (Verschoor, Spapé, Biro, &  
66 Hommel, 2013). These findings add to a growing body of work which demonstrates that both  
67 observational and motor experiences contribute to infants' emerging skills for processing and  
68 performing goal-directed actions.

69 Recently, researchers have begun to investigate whether, beyond segmentation, infants can also  
70 predict upcoming actions based on statistical learning. In a recent experiment, 18-month-old toddlers  
71 observed continuous action sequences with either deterministic or random transitional probabilities  
72 between actions. In a control condition, another group of toddlers observed the same sequence that  
73 featured self-propelled events rather than a human actor (Claire Monroy, Gerson, & Hunnius, 2017).  
74 Proportions of correct predictive looks preceding the deterministic actions increased over trials for  
75 the toddlers who observed the human actor, but not for those who observed the non-action visual  
76 events. These findings provided evidence that observing actions benefits action prediction, above and  
77 beyond observing non-action perceptual sequences. One possible explanation is that prior motor  
78 experiences with the observed actions contributed to the enhanced learning, as these actions were all  
79 within the motor capabilities of toddlers.

80 Support for this hypothesis comes from a growing body of evidence illustrating that action prediction  
81 is tightly coupled to infants' motor proficiency (Cannon, Woodward, Gredebäck, von Hofsten, &  
82 Turek, 2012; Gerson, Bekkering, & Hunnius, 2015; Gredebäck & Kochukhova, 2010; Kanakogi &  
83 Itakura, 2011). For instance, in one recent experiment, infant and adult participants watched videos of

84 other infants either crawling or walking across a room while their eye movements were recorded.  
85 Infants for whom crawling was their dominant form of locomotion predicted crawling more  
86 accurately than walking. In contrast, infants for whom walking was the dominant form of locomotion  
87 and adults were equally accurate at predicting both actions (Stapel, Hunnius, Meyer, & Bekkering,  
88 2016). Training studies—in which infants are given novel experience with actions they have never  
89 yet performed—immediately alter how infants subsequently perceive those actions (Gerson &  
90 Woodward, 2014; Sommerville, Woodward, & Needham, 2005). Together, these findings suggest  
91 that infants process actions more efficiently once the actions are more strongly established in their  
92 own motor repertoire.

93 Current theories propose that activation of the motor system during action observation is the most  
94 likely mechanism underlying efficient action prediction (Falck-Ytter et al., 2006; Flanagan &  
95 Johansson, 2003). In line with this claim, findings from neuroimaging studies reveal that motor  
96 regions in the brain are activated when infants observe others' actions. Activity in these regions is  
97 greater in response to actions with which infants have more motor experience, and are therefore more  
98 dominant in their motor repertoire, relative to actions with which they have less or no experience  
99 (Gerson et al., 2015; Southgate, Johnson, Karoui, & Csibra, 2010). In adults, motor activation is  
100 causally linked to predictive eye movements: introducing a competing motor task inhibits the ability  
101 to. Likewise, disrupting activity in the motor cortex via transcranial magnetic stimulation (TMS)  
102 impairs predictive eye movements, further suggesting that the motor system may even be necessary  
103 to successfully predict ongoing actions (C. Elsner, D'Ausilio, Gredebäck, Falck-Ytter, & Fadiga,  
104 2013).

105 Together, the current research shows that both observational statistical learning and action experience  
106 are central to infants' action understanding (Hunnius & Bekkering, 2014). To date, a few studies  
107 have attempted to compare the relative contributions of self-produced and observed actions on  
108 infants' action understanding (Gerson & Woodward, 2014) but none have examined how these two  
109 forms of experience might interact. We aimed to address this gap by asking whether newly acquired  
110 motor experience with grasping actions modulated infants' abilities to learn statistical regularities  
111 between those same actions when they were viewed in continuous sequences. In other words, if  
112 infants recruit motor representations when they observe actions they can perform, does this help them  
113 to more easily detect the sequential regularities between those actions during observation?

114 To tackle this question, we exploited infants' natural acquisition of a pincer grasp, a fine motor skill  
115 that emerges in the second half of the first year of life. Results from a prior study in our own lab  
116 indicated that the pincer grasp emerges between 8 and 11 months of age (Meyer, Braukmann, Stapel,  
117 Bekkering, & Hunnius, 2016). We thus expected 8- to 11-month-old infants to vary in the degree to  
118 which a whole hand (i.e., palmar) grasp and a pincer grasp were more dominant in their motor  
119 repertoire. In an eye-tracking experiment, infants were shown a video of an action sequence  
120 comprised of six possible object-directed actions. Within this sequence, there were two deterministic  
121 pairs in which one action always followed a second action with 100% probability and was followed  
122 by an effect. All other actions occurred in a random order. If infants learned the statistical structure of  
123 the action pairs, they should, in principle, make visual anticipations to the locations of the second  
124 action upon observing the first action (cf. Monroy et al., 2017). Both actions of one pair were  
125 performed with a pincer grasp, whereas both actions of the second pair were performed with a whole-  
126 hand grasp. Following the video, a grasp test was conducted to assess each infant's grasping  
127 proficiency.

128 We expected that, if infants learned the action pairs, they would make more visual anticipations  
 129 towards the second action and/or its effect than to any other object during the first action of an action  
 130 pair (i.e., a predictive time window). We also expected they would demonstrate an increase in  
 131 correct visual anticipations to the second actions as the sequence progressed (Monroy et al., 2017;  
 132 (Shafto, Conway, Field, & Houston, 2012). Finally, we hypothesized that infants would be better at  
 133 learning the statistical regularities for the action pairs more dominant in their current motor  
 134 repertoire. For example, we expected that those infants performing more whole-hand grasps, but not  
 135 yet performing pincer grasp actions, would anticipate the second action of the whole hand pair more  
 136 reliably than the pincer grasp pair. Infants for whom both actions are equally dominant in their motor  
 137 repertoire should not show preferential learning for one pair over the other.

## 138 2 Material and Methods

### 139 2.1 Participants

140 Forty-eight infants from 8 to 11 months of age were included in the final sample (Table 1). Infants  
 141 were recruited from a database of interested families from the surrounding region who volunteered to  
 142 participate. Seven additional infants were tested but excluded from the final sample due to calibration  
 143 errors ( $n = 1$ ) or failure to complete the observation phase due to excessive fussiness ( $n = 5$ ). One  
 144 infant made zero fixations on any of the trials of interest (i.e., the action pairs) and was also excluded  
 145 from analyses. The study was approved by the ethical committee of behavioral science at the Faculty  
 146 of Social Sciences in Nijmegen (Ethische Commissie Gedragwetenschappelijk Onderzoek;  
 147 ECG2012-1301-006). All subjects gave written informed consent in accordance with the Declaration  
 148 of Helsinki.

### 149 2.2 Stimuli

150 Video stimuli were created featuring a toy with multiple objects that could be manipulated in distinct  
 151 ways (Fig. 1A). An adult actor performed a continuous action sequence with the various objects on  
 152 the toy. For each action, the actor's hand entered the screen nearest to the object upon which she  
 153 would act, performed one action with that object (3s), and then left the screen. This was followed by  
 154 a brief pause (1s) before the next action began. Only the actor's hand was visible during each action.

155 Videos were divided into four blocks, with the viewing angle of the toy stimulus alternating between  
 156 blocks to ensure that spatial location did not become a predictable cue. Attention-getter clips (4s)  
 157 were played between blocks followed by a still frame (1s) of the toy (with no hand visible) to help  
 158 the infant reorient to the new perspective. The entire sequence lasted approximately seven minutes.  
 159 Engaging background music accompanied the video stimuli and was unrelated to the stimulus  
 160 presentation.

#### 161 2.2.1 Action sequence

162 The action sequence was structured as follows: two deterministic pairs were embedded within an  
 163 otherwise pseudorandomized order of six object-directed actions. One pair was performed with a  
 164 pincer grasp (Pincer pair) and consisted of the actions 'slide' followed by 'open'; the second pair was  
 165 performed with a whole-hand grasp (Hand pair) and consisted of 'bend' followed by 'push' (Fig.  
 166 1C). The second actions of the pairs were labeled the *target* actions, as these were the actions that  
 167 infants could learn to predict as they observed the unfolding sequence. Both pairs caused an action-  
 168 effect, which was a green or a pink colored light in the center of the toy that turned on at the midpoint  
 169 of the target actions. The light's two colors (green and pink) always corresponded to the same pairs

170 within one sequence. This matching was randomly counterbalanced across infants: one group always  
171 saw the Pincer pair activate a green light and the Hand pair activate a pink light, and the second  
172 group saw the reverse.

173 No action or pair occurred more than three times consecutively, and all elements (pairs and random  
174 actions) occurred with equal frequency. Target actions also occurred elsewhere in the sequence as  
175 random actions, to ensure that the effect only occurred after the two-step action pair and could not be  
176 independently associated with the target actions. Action sequences consisted of 96 total actions with  
177 12 trials of each pair (Pincer and Hand).

### 178 **2.2.2 Grasp test device**

179 Infants' grasping proficiency was assessed using a wooden apparatus (Fig 1B). A small and a large  
180 bead (3 and 5mm diameter) were attached to strings that were threaded through removable wooden  
181 panels which fit into the apparatus frame.

### 182 **2.3 Procedure**

183 The testing procedure consisted of an action observation phase followed by the grasp test. Infants  
184 were seated on a caretaker's lap throughout both phases. During the action observation phase, eye  
185 movements were recorded continuously with a Tobii T120 eye-tracker (Tobii Technologies, Inc.) at  
186 60Hz. Gaze was calibrated using a standard 9-point calibration procedure until at least 8 points were  
187 acquired or a maximum of three attempts. Immediately following calibration, infants were shown the  
188 video stimuli. Caretakers were requested to avert their gaze during calibration and to refrain from  
189 influencing their child during the observation phase.

190 After the sequence was completed (or until infants became too fussy to continue the observation  
191 task), caretakers and infants moved to a nearby table for the grasp test (adapted from the procedure of  
192 Meyer et al., 2016). The experimenter placed the test apparatus in front of the infant and performed a  
193 single demonstration of how to grasp the bead and pull it out. After returning the bead to its original  
194 position (Fig. 1B), infants were given one minute to pull out each bead. Each time they removed the  
195 bead, the experimenter replaced it and the infant could try again. This phase was videotaped from a  
196 camera placed with full view of the infant for offline behavioral analysis. In addition, a parental  
197 questionnaire was administered prior to the testing session with questions about infants' grasping  
198 history<sup>1</sup>.

## 199 **3 Data Analysis**

### 200 **3.1 Eye-tracking data**

201 Raw eye-tracking data was separated into discrete fixations using a custom software program (GSA;  
202 Philip van den Broek, Donders Institute) with a spatial filter of 30 pixels and a temporal filter of  
203 100ms. Regions of interest (ROIs) of equal size were defined around each object (i.e., action  
204 location) and around the action-effect (250 and 130 square pixels, respectively). Predictive time  
205 windows were defined as the four seconds from the first frame in which the hand appeared to  
206 perform the first action of a pair until the final frame just before the hand reappeared to perform the  
207 target (second) action (dashed bars; Fig. 1C).

---

<sup>1</sup>This was collected as a secondary measure to support the data from the grasp test and was not used in the current analyses.

208 **3.1.1 Calculation of proportions of predictive fixations**

209 Fixations to the target object and to the action-effect locations during predictive time windows were  
 210 considered correct, whereas fixations to any other object were considered incorrect. Fixations to the  
 211 location of ongoing actions were always excluded. We first calculated the proportions of correct (Eq.  
 212 1) and incorrect predictive fixations (Eq. 2) across all trials for each pair, divided the sum by the total  
 213 fixations made to all ROIs. Total incorrect fixations were divided by four to yield the average number  
 214 of fixations to an incorrect region; this measure has also been described elsewhere as an estimate of  
 215 chance (Tummeltshammer & Kirkham, 2013). Proportions of correct and incorrect fixations were  
 216 compared for each action pair, representing infants’ preference for anticipating a correct upcoming  
 217 action and/or its effect relative to the other object locations. Proportions of correct fixations (Eq. 1)  
 218 were also calculated per trial and analyzed using Generalized Estimating Equations (GEE) to  
 219 examine the emergence of predictive gaze over the course of the experiment. GEE analyses do not  
 220 apply list-wise exclusion of cases and are thus advantageous for analyzing data with repeated  
 221 measures that contain missing points, such as trials in which no anticipatory fixations occur (Zeger,  
 222 Liang, & Albert, 1988).

223 
$$\text{Correct} = \frac{\# \text{ fixations to target \& effect}}{\text{total \# fixations to all ROIs}} \quad (1)$$

224 
$$\text{Incorrect} = \frac{\# \text{ fixations to 4 non-target objects}/4}{\text{total \# fixations to all ROIs}} \quad (2)$$

225 Equations 1-2: Calculations of the proportion measures. ‘All ROIs’ refers to the six objects and the  
 226 action-effect.

227 **3.2 Grasp test**

228 Infants’ ability to pull the beads out of the panels served as our measure of grasp proficiency (Fig. 2).  
 229 Video recordings of the grasp test phase were coded offline by a coder who was blind to the aims of  
 230 the study. Each attempt to extract the bead from the device was coded as hand grasp, a transitional  
 231 (i.e., inferior pincer) grasp, or a pincer grasp. Next, we calculated the proportion of times infants used  
 232 each grasp type out of the total number of times he or she successfully extracted the beads, collapsed  
 233 across small and large beads. Unsuccessful attempts were not coded.

234 Almost all infants could extract the bead from the device, while demonstrating different levels of  
 235 grasping competence to do so. We thus classified infants according to the type of grasp they used  
 236 most frequently to extract the bead, reasoning that this would reflect the motor ability most dominant  
 237 in their current repertoire. Rather than acquiring new motor skills in sudden steps, infants’ motor  
 238 skills emerge in a gradual, graded way (see Ambrosini et al., 2013 for another non-binary scoring  
 239 method). Each infant was classified as *Pincer-dominant*, *Hand-dominant*, or *Transitional* depending  
 240 on which grasp they used most (Table 1). For instance, if the relative proportions of an infant’s  
 241 grasping actions were 0.58, 0.25, and 0.17 (pincer, transitional, and hand, respectively) this infant  
 242 would be classified as a *Pincer-dominant* infant. Infants whose relative proportions were evenly  
 243 distributed across grasp types—such as 0.33, 0.33 and 0.34—were also classified as *Transitional*  
 244 infants. To avoid confusion, infant groups (*Pincer-dominant*, *Hand-dominant*, and *Transitional*) are  
 245 presented in italics and action pairs (Pincer, Hand) in non-italics.

246 **4 Results**

247 **4.1 Age effects**

248 A one-way ANOVA with age as dependent variable and Motor Group as a factor indicated that mean  
 249 age differed significantly among the three motor groups,  $F(2,47) = 3.89$ ,  $p = .03$  (see Table 1).  
 250 Pairwise comparisons revealed that the *Pincer-dominant* infants were significantly older than the  
 251 *Hand-dominant* groups (mean difference [ $MD$ ] = 27.96 days,  $p = .01$ ) and the *Transitional* group  
 252 ( $MD = 24.00$  days;  $p = .02$ ). There were no differences between the *Hand-dominant* and the  
 253 *Transitional* infants ( $MD = 3.96$ ,  $p = .66$ ).

## 254 4.2 Visual Attention

255 There were no differences between infant groups in overall looking time to all regions of interest  
 256 throughout the entire video, or in the total number of fixations during predictive time windows ( $ps >$   
 257  $.25$ ). Thus, infants with different levels of motor experiences did not demonstrate different visual  
 258 attention to the action sequence. Across groups, infants made anticipatory fixations to the target  
 259 actions on 28.3% of the experimental trials for which gaze data was obtained across both pairs. This  
 260 rate of anticipatory looks is typical for infants in this age range (Tummeltshammer & Kirkham,  
 261 2013).

262 To assess rates of anticipations over the course of the experiment, we conducted a linear, model-  
 263 based GEE with an unstructured working correlation matrix. Each of the 12 trials from each pair  
 264 (Pincer, Hand) was assigned a 1 if it included anticipation and a 0 if not. Trials were then collapsed  
 265 into four time bins with three trials in each bin. Pair (Pincer, Hand) and Time Bin (T1, T2, T3, T4)  
 266 were entered as within-subjects repeated measures and Motor Group (*Pincer-dominant*, *Transitional*,  
 267 *Hand-dominant*) was entered as a between-subjects factor. Across all infants, rates of anticipation  
 268 decreased significantly over the course of the experiment,  $\chi^2(3) = 51.14$ ,  $p < .001$ . Pairwise  
 269 comparisons revealed a consistent statistically significant decrease in the proportion of trials  
 270 containing predictive fixations from each Time Bin to the next (e.g., from T1 to T2, from T2 to T3  
 271 and from T3 to T4). There were no other main effects or interactions ( $ps > .17$ ), indicating that rates  
 272 of visual attention did not differ across infants based on age or motor abilities.

## 273 4.3 Correct vs. Incorrect

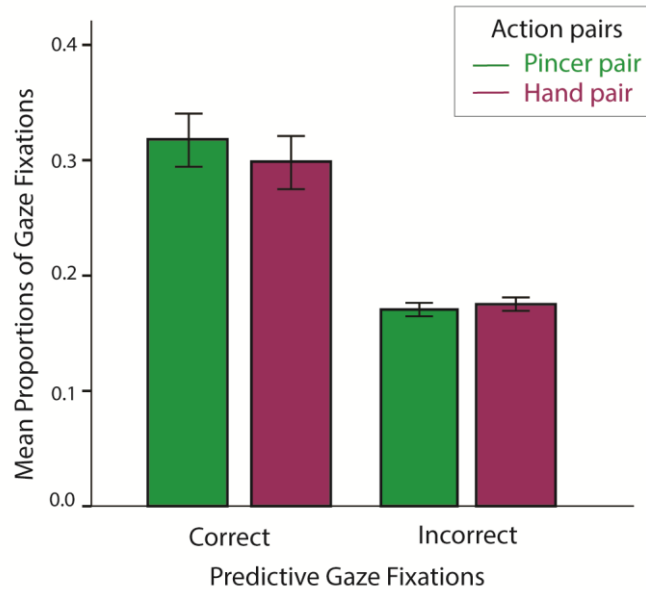
274 A one-sample Kolmogorov-Smirnov test revealed that proportion scores did not differ from a normal  
 275 distribution for all dependent variables ( $ps > .05$ ). A Levene's test confirmed that the variances  
 276 between the motor groups did not significantly differ from one another,  $p > .05$ .

277 To assess whether infants anticipated the next events in the sequence, we first compared proportions  
 278 of correct fixations (Eq. 1) relative to incorrect fixations (Eq. 2) across the duration of the  
 279 experiment. If infants learned the action pairs, proportions of fixations to correct locations should be  
 280 higher than proportions to incorrect locations. In this analysis, the first trial was always excluded  
 281 from calculations, as infants should not be able to correctly predict on the very first observation of  
 282 each pair.

283 We first compared correct and incorrect fixations across all infants to assess whether learning  
 284 occurred at all. An ANOVA with Prediction (Correct vs. Incorrect) and Pair (Pincer, Hand) as  
 285 within-subject factors and age as a covariate revealed a marginally significant main effect of  
 286 Prediction,  $F(1,43) = 3.04$ ,  $\eta_p^2 = .07$ ,  $p = .09$  and a significant effect of age,  $p = .04$ . Without age as a  
 287 covariate, the main effect of Prediction was significant,  $F(1,46) = 22.08$ ,  $\eta_p^2 = .32$ ,  $p < .001$  (Fig. 3).  
 288 Across pairs, correct proportions were higher than incorrect proportions ( $MD = .14$ ,  $SEM = .03$ ,  $p <$



289 | .001)<sup>2</sup>. There was no main effect of pair ( $p = .64$ ) nor was there an interaction between Pair and  
 290 Prediction ( $p = .64$ ).



291

292 | Figure 3: The mean proportions of correct and incorrect gaze fixations collapsed across motor  
 293 groups. Bars represent standard errors of the mean.

294 We next added Motor Group (*Pincer-dominant, Transitional, Hand-dominant*) as a between-subjects  
 295 factor to assess whether correct and incorrect fixations varied among motor groups with age as a  
 296 covariate. This yielded no main effects or interactions with Motor Group ( $ps > .60$ ). Thus, as a group,  
 297 infants selectively anticipated the correct action and its effects more frequently than they incorrectly  
 298 anticipated other objects on the screen across all trials, and this did not significantly differ between  
 299 pairs or motor groups.

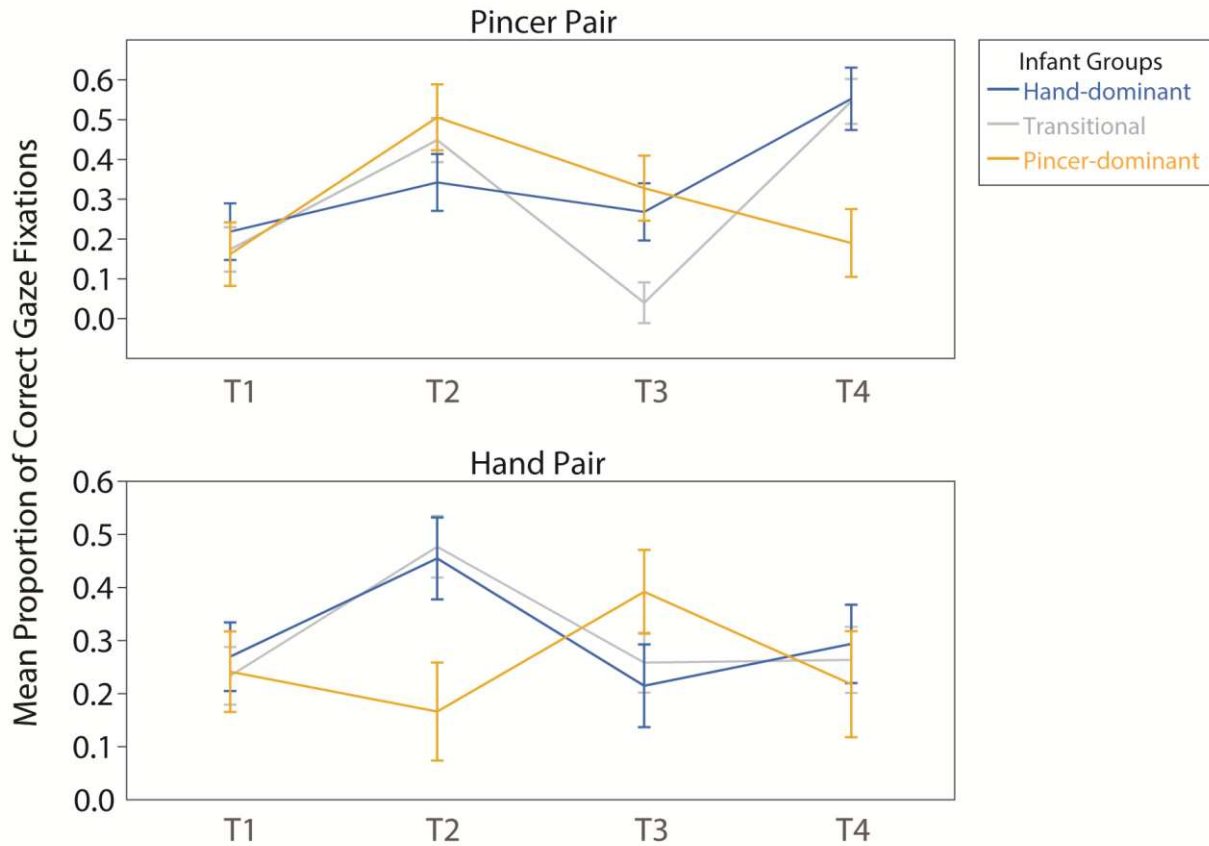
300 **4.4 Learning over time**

301 To further probe infants' predictive gaze behaviors, we examined correct gaze proportions over time.  
 302 We expected proportions of correct fixations (Eq.1) to increase over trials, as infants learned the  
 303 sequence regularities. Correct fixations were entered into a linear, model-based GEE with an  
 304 unstructured Working Correlation Matrix. Pair (Pincer, Hand) and Time Bin (T1, T2, T3, T4) were  
 305 entered as within-subjects repeated measures and Motor Group (*Pincer-dominant, Transitional,*  
 306 *Hand-dominant*) was entered as a between-subjects factor. Age was included as a covariate. The  
 307 GEE revealed a significant main effect of Time Bin,  $\chi^2(3) = 31.00, p < .001$ , a significant interaction  
 308 between Pair and Time Bin,  $\chi^2(3) = 15.047, p = .002$ , a significant interaction between Motor Group  
 309 and Time Bin,  $\chi^2(6) = 23.33, p = .001$ , and a significant 3-way interaction between Pair, Motor  
 310 Group and Time Bin,  $\chi^2(6) = 22.98, p = .001$ . There was no main effect of age,  $p = .16$ .

---

<sup>2</sup>Due to the uneven and relatively small sizes of our participant groups and relatively small samples, we repeated this analysis using a non-parametric Wilcoxon Signed Ranks test to compare Correct and Incorrect fixations across pairs and motor groups. This analysis confirmed that the mean proportion of Correct fixations was significantly greater than the proportion of Incorrect fixations,  $z = -3.91, p < .001, r = -0.56$ .

311 To assess whether the time-course of learning differed among motor groups, pairwise comparisons  
 312 were conducted to follow up on the significant 3-way interaction between Pair, Motor Group, and  
 313 Time Bin. This interaction effect is illustrated in Figure 4. Based on our *a priori* hypotheses, we  
 314 expected the largest differences in predictive gaze between *Pincer-dominant* and *Hand-dominant*  
 315 infants. Therefore, we first focus on the results from follow-up comparisons between these two  
 316 groups, before turning to the results from the *Transitional* group.



317  
 318 Figure 4: The mean proportion of correct gaze fixations over the four time bins of the experiment  
 319 plotted separately for the Pincer pair (above) and the Hand pair (below). Lines represent the three  
 320 infant motor groups. Bars represent standard errors.

321 For the *Pincer-dominant* motor group, correct predictions to the Pincer pair sharply increased from  
 322 T1 to T2 ( $MD = .34$ ,  $SEM = .12$ ,  $p = .003$ ) and then subsequently decreased from T2 to T4 ( $MD = .32$ ,  
 323  $SEM = .10$ ,  $p = .002$ ). In contrast, the *Hand-dominant* group demonstrated no such increase in correct  
 324 proportions from T1 to T2 ( $MD = .12$ ,  $SEM = .10$ ,  $p = .23$ ). However, there were no differences  
 325 between *Pincer-* and *Hand-dominant* groups for the Pincer pair at either T1 or T2 ( $ps > .14$ ). It was  
 326 not the case that the *Hand-dominant* infants showed no evidence for learning of the Pincer pair, as  
 327 they did improve from T1 to T4 ( $MD = .33$ ,  $SEM = .10$ ,  $p = .001$ ), but this increase was slower than  
 328 that of the *Pincer-dominant* infants and did not emerge until the final quarter of the trials.

329 For the Hand pair, the pattern was reversed: the *Pincer-dominant* infants showed no difference in  
 330 correct predictions from T1 to T2 ( $MD = .08$ ,  $SEM = .12$ ,  $p = .53$ ) whereas correct predictions  
 331 increased marginally for the *Hand-dominant* infants ( $MD = .19$ ,  $SEM = .10$ ,  $p = .07$ ). There was no  
 332 difference between *Pincer-dominant* and *Hand-dominant* groups for the Hand pair at T1 ( $MD = .03$ ,

333  $SEM = .10, p = .78$ ); however, they did differ significantly at T2 ( $MD = .29, SEM = .12, p = .017$ ).  
 334 The *Hand-dominant* infants subsequently showed a decrease in correct predictions from T2 to T3  
 335 ( $MD = .24, SEM = .10, p = .016$ ) and no significant gain across the experiment (T1 to T4; ( $MD = .02,$   
 336  $SEM = .09, p = .80$ ). The *Pincer-dominant* infants also showed no significant gain across the  
 337 experiment for the Hand pair ( $MD = .02, SEM = .12, p = .85$ ).

338 The *Transitional* group demonstrated a pattern in between that of the *Pincer-dominant* and the *Hand-*  
 339 *dominant* group. For the Pincer pair, the transitional group also increased their correct fixations from  
 340 T1 to T2 like the *Pincer-dominant* group ( $MD = .27, SEM = .08, p = .001$ ), followed by a decrease  
 341 from T2 to T3 ( $MD = -.41, SEM = .08, p < .001$ ). However, they again showed a second rise in  
 342 correct predictions from T3 to T4 ( $MD = .51, SEM = .06, p < .001$ ), like the *Hand-dominant* group,  
 343 and overall their correct predictions increased from T1 to T4 ( $MD = .37, SEM = .08, p < .001$ ). For  
 344 the Hand pair, the transitional group closely followed the pattern of the *Hand-dominant* infants, with  
 345 an initial gain in correct anticipations from T1 to T2 ( $MD = .24, SEM = .08, p = .003$ ) followed by a  
 346 decrease from T2 to T3 ( $MD = -.22, SEM = .07, p = .002$ ), and no significant change across the entire  
 347 experiment (T1 to T4;  $MD = .03, SEM = .08, p = .70$ ).

348 To sum up, the infants with more dominant pincer grasp abilities quickly detected the pair structure  
 349 for actions performed with a pincer grasp and correctly anticipated the upcoming action or its effect  
 350 within the first few observations. This was then followed by a decrease in correct predictions in later  
 351 trials. Similarly, the infants with a dominant hand grasp showed a faster improvement in predictions  
 352 for the actions performed with a hand grasp, followed by a decline in performance. The *Transitional*  
 353 infants, whose motor experience fell between *Hand-dominant* and *Pincer-dominant* infants, showed  
 354 fixation patterns which shared characteristics with both groups.

## 355 5 Discussion

356 Observational statistical learning and motor experiences are both key pathways to infants' developing  
 357 action understanding and social-cognitive abilities (Hunnius & Bekkering 2014). In the current eye-  
 358 tracking experiment, we aimed to shed light on how these processes interact with one another during  
 359 action observation. Infants observed an action sequence containing two deterministic pairs, one  
 360 performed with a pincer grasp and the other with a whole-hand grasp. Predictive gaze to the second  
 361 actions of each pair and their associated effects were measured as an indicator of statistical learning.  
 362 Following observation, infants' motor performance on a grasp test was used to determine their  
 363 dominant grasp type. Our central hypothesis was that learning would be modulated by infants' level  
 364 of motor proficiency with the observed grasp type.

365 Findings revealed that infants, as a group, learned the transitional probabilities within the observed  
 366 action sequences. Across pairs and motor groups, infants made more fixations to the correct  
 367 upcoming actions and/or their effects than to other action locations on the screen. Consistent with  
 368 prior findings with older infants (Monroy, Gerson & Hunnius, 2017), these results show that 8- to 11-  
 369 month-olds can predict upcoming actions and their effects by learning transitional probabilities  
 370 within an action sequence. Further, the general ability to predict upcoming actions was not driven by  
 371 the specific motor action observed or by infants' levels of motor proficiency.

372 A direct link between infants' action perception and action production has previously been  
 373 demonstrated for simple, isolated actions such as reaching and grasping (e.g., Gredebäck and  
 374 Kochukhova, 2010; Kanakogi and Itakura, 2011). In the current experiment, we examined whether  
 375 this link extends to situations in which infants need to use their statistical learning skills to predict

376 upcoming sequential actions. This would be consistent with motor-based accounts of action  
 377 understanding, which hypothesize that the motor system guides the generation of action predictions  
 378 (Kilner, Friston, & Frith, 2007).

379 Our data provide partial support for the notion that recent motor experiences influence infants'  
 380 statistical learning for action sequences. However, they do not provide conclusive support for the  
 381 hypothesis that motor-based learning is essential for action predictions. Results showed that infants  
 382 with a dominant pincer-hand grasp demonstrated an early increase in correct anticipations for the  
 383 pincer grasp but not the hand grasp, indicating faster learning for the action dominant in their current  
 384 motor repertoire. Likewise, infants with a dominant whole-hand grasp similarly demonstrated an  
 385 early increase in correct anticipations for the hand grasp, but not the pincer grasp. The transitional  
 386 infants—who likely had similar levels of proficiency with both actions—shared similar patterns with  
 387 both groups. In sum, infants' ability to learn action pairs based on statistical regularities was faster  
 388 for the actions that are dominant in their current motor repertoire.

389 Faster learning for the action pair matching infants' own motor abilities may reflect the influence of  
 390 motor experiences on the ability to predict upcoming sequential actions, as we had hypothesized.  
 391 According to motor-based accounts, the motor system combines prior knowledge with incoming  
 392 sensory input to generate a prediction (Kilner et al., 2007). Motor experiences with the observed act  
 393 are one important source of prior knowledge and allow the motor system to generate more precise  
 394 predictions (Stapel et al., 2016). According to these views, the current data show that infants more  
 395 readily predicted the actions for which they could recruit an established motor representation.

396 Unexpectedly, infants with a dominant whole-hand grasp, who had little experience performing a  
 397 pincer grasp, still demonstrated learning for the pincer grasp pair. These findings suggest that the  
 398 motor system was not the critical driving factor in infants' action processing. However, there were  
 399 three principal differences between the current experiment and the previous evidence for a closer link  
 400 between motor skills and action prediction skills (e.g., Ambrosini et al., 2013; Gredebäck &  
 401 Kochukhova, 2010; Kanakogi & Itakura, 2011). First, our paradigm featured sequential actions that  
 402 differed in both statistical likelihood and type of grasp, whereas previous studies featured isolated  
 403 reaching actions that differed only in the observed grasp. A recent study with adults revealed that,  
 404 when action sequences contain varying degrees of predictability between actions, non-motor neural  
 405 networks are activated that are traditionally involved in processing uncertainty within probabilistic  
 406 perceptual input (Ahlheim, Stadler, & Schubotz, 2014). In a similar vein, perceptually difficult  
 407 conditions engage additional brain regions beyond those typically activated during action observation  
 408 (Lingnau & Petris, 2013). Thus, under uncertainty, domain-general regions outside the action-  
 409 observation network become involved. One possibility is that additional non-motor processes became  
 410 involved when infants' own motor system does not have enough knowledge or sensory information  
 411 to generate a precise prediction.

412 Secondly, prior research investigating anticipatory gaze and motor abilities have measured  
 413 anticipations to the target, or end-point, of the actor's reach-to-grasp actions. For instance, in  
 414 Ambrosini et al., 2013, fixations during an actor's reaching movement were recorded and  
 415 anticipations were defined as any fixation to the object before the hand made contact. In this study,  
 416 infants with faster anticipations to the object were considered more predictive than infants who  
 417 anticipated later (see also Falck-Ytter et al., 2006; Gredebäck & Kochukhova, 2010; Kanakogi and  
 418 Itakura, 2011; Rosander and von Hofsten, 2011). Some have interpreted such findings as evidence  
 419 for the influence of an internal motor program, indicated by faster visual anticipations during the  
 420 movement trajectory of observed action (i.e., a 'gaze advantage', Rosander & von Hofsten, 2011). In

421 the current experiment, we assessed anticipations to a future action step, rather than speed of gaze  
422 latencies during a reaching phase in which multiple motor cues are immediately available—such as  
423 movement velocity, hand shape and trajectory. Possibly, the difference between our findings and  
424 those of the aforementioned studies could indicate that motor experiences have a lesser impact on  
425 predicting the identity of an upcoming action step that cannot be predicted solely based on incoming  
426 motor information.

427 A third important difference between the current study and most prior research is our method of  
428 classifying motor ability. Here, we classified infants based on the relative dominance of each grasp  
429 type, rather than a binary classification of whether infants could in general perform the action or not  
430 (e.g., van Elk et al., 2008). This method more closely mirrors how infants' motor development  
431 naturally unfolds (Ambrosini et al., 2013). Infants accumulate both visual and motor experiences  
432 with the fine-grained kinematics of an action—such as a certain muscle movement—before piecing  
433 together the entire action skill (Senna et al., 2016). Thus, although the whole-hand infants do not yet  
434 readily or voluntarily perform a pincer grasp, they may be able to take advantage of finer-grained  
435 motor cues for movements that they can do, such as the actor's hand shape (Ambrosini et al., 2013).  
436 Indeed, some motor-based accounts claim that the motor system can predict even those actions well  
437 outside our own physical abilities—such as a bird's flight—by approximating the link between the  
438 observed act and the motor system's internal model (Schubotz, 2007).

439 Recent studies have further probed the influence of developing motor abilities on infants' visual  
440 attention to actions and the objects and effects related to them. Importantly, shifts in visual attention  
441 may relate to the nature of what is attended to, rather than simply the overall amount. Though we  
442 observed no differences in global attention to objects between motor groups, there may have been  
443 differences in the microstructure of infants' gaze shifts which could have led them to receive altered  
444 visual inputs according to the congruency between the observed action pair and their own motor  
445 expertise. For instance, Smith and colleagues (Smith & Yu, 2008; Yu & Smith, 2011) used  
446 microanalytic techniques to show that infants' learning outcomes related to fine-grained patterns of  
447 gaze shifts between objects, and could be modelled by a simple associative learning model. Although  
448 in the current study we restricted our analyses to only predictive gaze, further analysis of the relations  
449 between fine-grained measures of visual attention and motor abilities would be an interesting avenue  
450 for future research and may shed additional light on the observed patterns.

451 Along these same lines, in the current study we considered predictions to upcoming actions and their  
452 effects as correct. We did not investigate whether infants only predicted the effect instead of the next  
453 upcoming action. Prior research has shown that infants of a similar age range rely on cues from  
454 action-effects to learn about sequential outcomes (Monroy et al., 2017; Verschoor, Weidema, Biro, &  
455 Hommel, 2010). It has also been suggested that the motor system predicts the effects of our own  
456 actions and those that we observe (Elsner et al., 2002). Thus, though it was not the focus of the  
457 current study, it would be interesting to further investigate whether the presence of action-effects  
458 might be an important aspect of the relation between motor experiences and statistical learning.

459 Surprisingly, following the initial rise in correct predictions for actions matching their own motor  
460 abilities, correct predictions subsequently declined. This decline was consistent across all infants and  
461 across action pairs, and showed that predictions did not follow a stable pattern over time. One simple  
462 explanation is a loss of attention to the stimuli. The proportions of trials containing predictive gaze  
463 fixations steadily decreased over the course of the experiment, indicating that infants made fewer  
464 predictions during later trials. Infants may have simply stopped anticipating after successfully  
465 making a few correct predictions, given that no new information was offered by subsequent

466 repetitions of the action pairs. They may instead have begun to engage in other visual behaviors such  
467 as tracking the actor's hands or exploring the visual scene in search of novel information. Some  
468 paradigms use so-called 'occluders' to encourage participants to make visual anticipations (e.g.,  
469 Falck-Ytter et al., 2006; Hunt and Aslin, 2001; Johnson et al., 2003; Paulus et al., 2011). In contrast,  
470 in our study, all objects were freely visible throughout the entire demonstration which, though more  
471 ecologically valid, may also have 'discouraged' anticipatory gaze. The conditions under which  
472 infants reliably and consistently anticipate actions, particularly in naturalistic, live contexts, are an  
473 important avenue for future research which we are currently pursuing.

### 474 **5.1 Conclusion**

475 Given the accumulating evidence for the role of the motor system in facilitating action processing,  
476 can motor accounts explain the current findings? We propose that infants were engaging their motor  
477 systems as they processed the action sequence: when the observed action pairs were congruent with  
478 the grasping action most dominant in their motor repertoire, infants demonstrated a rapid increase in  
479 correct predictions. However, differences between motor groups were subtle. Learning was not  
480 tightly constrained by infants' level of motor expertise, suggesting that additional cognitive processes  
481 come into play when infants need to use their statistical learning skills to generate action predictions.  
482 These findings further demonstrate that infants' action prediction abilities cannot solely be explained  
483 by motor accounts, but likely reflect the recruitment of both motor and non-motor strategies when  
484 prediction requires learning statistical regularities in action sequences.

### 485 **6 Conflict of Interest**

486 *The authors declare that the research was conducted in the absence of any commercial or financial*  
487 *relationships that could be construed as a potential conflict of interest.*

### 488 **7 Author Contributions**

489 CM led the writing of this manuscript. CM, SG and SH designed the experimental paradigm. CM  
490 collected the data and conducted the analyses. SG and SH both provided supervision and discussion  
491 regarding the analyses. SG and SH reviewed and contributed edits to this manuscript.

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## 632 11 Figure Legends

633 Figure 1: A. Example frame from the video stimuli, in which an adult performed a continuous  
 634 sequence of actions with the six possible objects on the toy. B. Following observation, infants'  
 635 grasping abilities were assessed using the pictured apparatus, which required them to extract the bead  
 636 from the wooden board. C. Schematic illustrating the statistical structure of the action sequence  
 637 containing two deterministic pairs that caused a light effect: one pair was performed with a pincer  
 638 grasp and the second with a whole-hand grasp. Numbers represent transitional probabilities between  
 639 paired and random actions. Dotted lines underneath the first action of a pair depict the 4s period  
 640 preceding the target actions in which predictive gaze fixations were analyzed.

641 Figure 2: Illustrations depicting classification of grasping actions into whole hand (A), transitional  
 642 (B), or pincer (C) grasps during the grasp test. Only (C) was considered a true pincer grasp as this  
 643 action requires opposition of the thumb and forefinger. Image modified with permission from  
 644 (Erhardt, 1994).

645 Figure 3: The mean proportion of correct gaze fixations collapsed across motor groups. Bars  
 646 represent standard errors of the mean.

647 Figure 4: The mean proportion of correct gaze fixations over the four time bins of the experiment  
 648 plotted separately for the Pincer pair (above) and the Hand pair (below). Lines represent the three  
 649 infant motor groups. Bars represent standard errors.

## 650 12 Tables

651 Table 1

652 Characteristics of the final sample.

Sample characteristics				Grasp test measures			
Motor group	<i>n</i>	Mean age in months ( <i>sd</i> )	Gender (f:m)	Mean prop. pincer grasps ( <i>sd</i> )	<u>Mean prop. transitional grasps (<i>sd</i>)</u>	Mean prop. hand grasps ( <i>sd</i> )	Mean span in months* ( <i>sd</i> )
<i>Pincer-dominant</i>	11	10.86 (0.63)	6:5	0.65 (0.17)	<u>0.17 (0.11)</u>	0.18 (0.13)	2.65 (1.58)
<i>Transitional</i>	22	10.07 (0.94)	6:16	0.21 (0.16)	<u>0.45 (0.30)</u>	0.35 (0.25)	1.93 (1.10)
<i>Hand-dominant</i>	15	9.94 (0.97)	7:8	0.06 (0.08)	<u>0.13 (0.11)</u>	0.80 (0.10)	1.65 (0.90)

653 \*number of months since infant first used a pincer grasp, per parent report (for descriptive purposes  
 654 only; not used in analyses.