Infants' motor proficiency and statistical learning for actions

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Abstract

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

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, Gredeback, 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 Gedragswetenschappelijk 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[1].

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).

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[1]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
$$\text{Correct} = \frac{\text{\# fixations to target \& effect}}{\text{total \# fixations to all ROIs}} \tag{1}$$

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

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, $\chi2(3)$ = 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)[2]. There was no main effect of pair ($p = .64$) nor was there an interaction between Pair and
290   Prediction ($p = .64$).
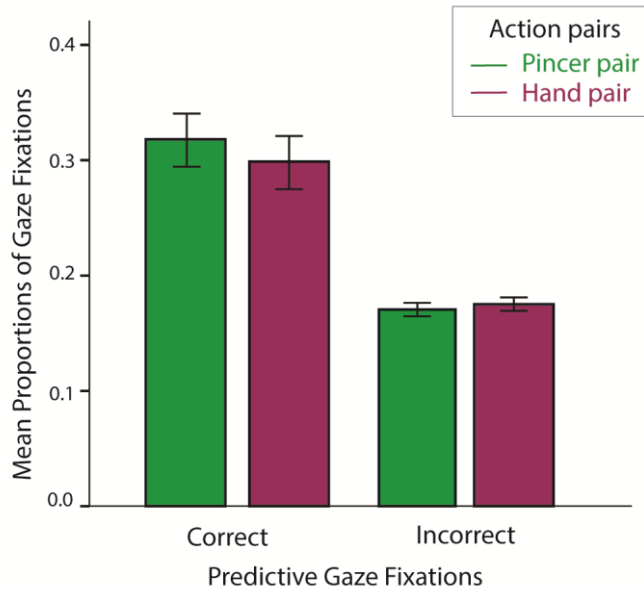
291

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, $\chi2(3) = 31.00$, $p < .001$, a significant interaction
308   between Pair and Time Bin, $\chi2(3) = 15.047$, $p = .002$, a significant interaction between Motor Group
309   and Time Bin, $\chi2(6) = 23.33$. $p = .001$, and a significant 3-way interaction between Pair, Motor
310   Group and Time Bin, $\chi2(6) = 22.98$, $p = .001$. There was no main effect of age, $p = .16$.

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[2]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.
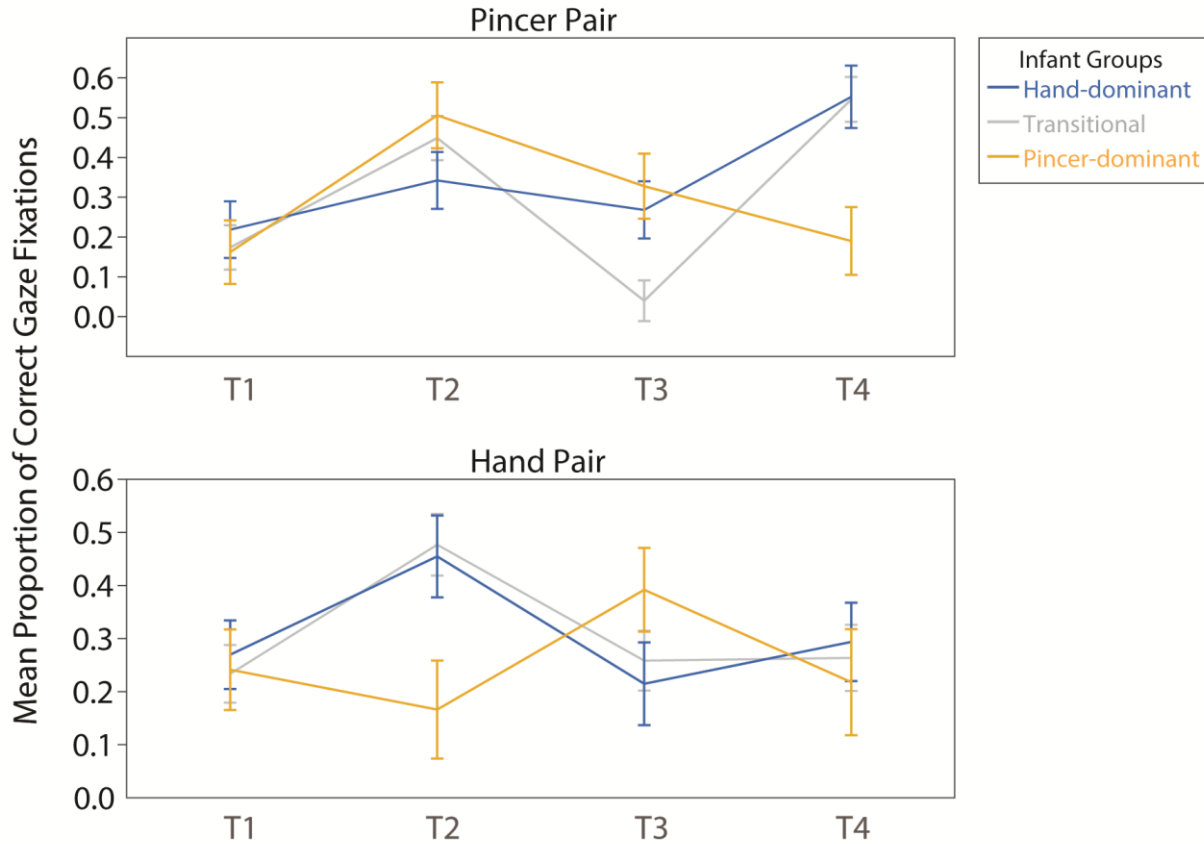
317

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,

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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**

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	*n*	Mean age in months *(sd)*	Gender (f:m)	Mean prop. pincer grasps *(sd)*	Mean prop. transitional grasps (*sd*)	Mean prop. hand grasps *(sd)*	Mean span in months* *(sd)*
Pincer-dominant	11	10.86 *(0.63)*	6:5	0.65 *(0.17)*	0.17 *(0.11)*	0.18 *(0.13)*	2.65 *(1.58)*
Transitional	22	10.07 *(0.94)*	6:16	0.21 *(0.16)*	0.45 *(0.30)*	0.35 *(0.25)*	1.93 (*1.10*)
Hand-dominant	15	9.94 *(0.97)*	7:8	0.06 *(0.08)*	0.13 *(0.11)*	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.