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Citation for final published version:

Monroy, Claire D., Gerson, Sarah A. , Dominguez-Martinez, Estefania, Kaduk, Katharina, Hunnius, Sabine and Reid, Vincent 2019. Sensitivity to structure in action sequences: An infant event-related potential study. *Neuropsychologia* 126 , pp. 92-101. 10.1016/j.neuropsychologia.2017.05.007

Publishers page: <https://doi.org/10.1016/j.neuropsychologia.2017.05...>

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1 Running head: SENSITIVITY TO ACTION STRUCTURE: AN INFANT ERP STUDY

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5 Sensitivity to structure in action sequences: An infant event-related potential study

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1 Highlights

- 2 • EEG and eye-tracking were recorded while 8-11-month-old infants observed action
3 sequences containing statistical regularities
- 4 • Infants demonstrated sensitivity to statistical regularities in action sequences in both
5 predictive gaze behavior and event-related potential components
- 6 • Violations of statistical regularities elicited a Negative central component, a marker of
7 infant visual attention
- 8 • Infants' depend on the presence of action-effects to detect the statistical regularities in
9 other people's action sequences

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Abstract

1 Infants are sensitive to structure and patterns within continuous streams of sensory
2 input. This sensitivity relies on statistical learning, the ability to detect predictable regularities
3 in spatial and temporal sequences. Recent evidence has shown that infants can detect
4 statistical regularities in action sequences they observe, but little is known about the neural
5 process that give rise to this ability. In the current experiment, we combined
6 electroencephalography (EEG) with eye-tracking to identify electrophysiological markers that
7 indicate whether 8-11-month-old infants detect violations to learned regularities in action
8 sequences, and to relate these markers to behavioral measures of anticipation during learning.
9
10 In a learning phase, infants observed an actor performing a sequence featuring two
11 deterministic pairs embedded within an otherwise random sequence. Thus, the first action of
12 each pair was predictive of what would occur next. One of the pairs caused an action-effect,
13 whereas the second did not. In a subsequent test phase, infants observed another sequence that
14 included deviant pairs, violating the previously observed action pairs. Event-related potential
15 (ERP) responses were analyzed and compared between the deviant and the original action
16 pairs. Findings reveal that infants demonstrated a greater Negative central (Nc) ERP response
17 to the deviant actions for the pair that caused the action-effect, which was consistent with
18 their visual anticipations during the learning phase. Findings are discussed in terms of the
19 neural and behavioral processes underlying perception and learning of structured action
20 sequences.

21

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23 Keywords: statistical learning, infant event-related potentials, action sequences, eye-tracking,
24 social-cognitive development

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1 Sensitivity to structure in action sequences: An infant event-related potential study

2 **1.0 Introduction**

3 Infants face the constant challenge of perceiving meaningful events within the
4 complex action sequences they observe. Human actions contain inherent statistical
5 regularities, characterized by predictable patterns that result in specific goals or outcomes. For
6 instance, the everyday action of ‘drinking tea’ always consists of the same sequence: grasping
7 a kettle, heating water, adding milk (if you are British), and so forth. Sensitivity to sequential
8 regularities forms the basis for the ability to predict action goals, their outcomes, and to
9 adaptively respond during social interactions. In fact, infant’s growing abilities to understand
10 the social world may arise initially from their statistical learning skills (Ruffman et al., 2012).

11 Recent studies have investigated infants’ sensitivity to different kinds of statistical
12 information in actions they observe. Paulus and colleagues (2011) showed that 9-month-olds
13 used frequency information from prior observations to predict where an agent would reappear
14 along a path after disappearing (Paulus et al., 2011). In another experiment (Stahl et al.,
15 2014), 18-month-olds viewed action sequences comprised of three-step deterministic action
16 ‘units’ (example: A-B-C and D-E-F). Afterwards, they were tested on their ability to
17 discriminate intact units (A-B-C) and ‘part-units’, which featured lower transitional
18 probabilities (example: C-D-E). Their results showed that 18-month-olds successfully
19 discriminated between units and part-units, indicating that they successfully segmented the
20 action sequence according to its transitional probabilities.

21 Further behavioral studies show that infants can detect regularities in visual events and
22 actions from the statistical information alone, independently from physical or movement cues
23 (Baldwin et al., 2001; Hespos et al., 2009; Kirkham et al., 2002; Saylor et al., 2007). One
24 hypothesis arising from this evidence is that infants initially rely on statistical learning skills
25 to predict upcoming events based on sequential regularities, and that these skills precede the

1 ability to form conceptual expectations about goal-directed actions (Hunnius and Bekkering,
2 2014). In other words, infants first learn that someone grasping a mug typically pours tea
3 before drinking, which in turn enables them to predict that the mug will be brought to the
4 mouth, and ultimately leads to a meaningful concept of the act of ‘drinking tea’.

5 The sensory consequences of an action—action-effects—are a central feature of goal-
6 directed action. As in the tea example, each step is associated with a change in the sensory
7 environment such as the sound of the pouring tea. The development of infants’ understanding
8 of goal-directed actions may primarily emerge through repeated observation of actions and
9 their perceptual effects (Hunnius & Bekkering, 2014). Prior behavioral studies illustrate that
10 action-effects are critical in guiding how infants perceive and learn about action events
11 (Jovanovic et al., 2007; Klein et al., 2006; Verschoor et al., 2010). However, though they may
12 enhance learning or induce changes in behavior, action-effects may not be necessary for
13 infants to initially learn the regularities in observed action sequences. Some research has
14 shown that infants and adults demonstrate neural responses to sequential events based only on
15 their statistical likelihood (Abla & Okanoya, 2009; Teinonen et al., 2009). Given these
16 findings there is no reason to expect infants could not do so for action sequences as well,
17 though they might acquire a stronger association between sequential actions that cause action-
18 effects for several reasons. First, infants are drawn to contingency, and action-effects are
19 salient sensory events that are also contingent upon the action causing them (Gergely &
20 Watson, 1999, 1996). Second, action-effects may be perceived as goals and draw attention to
21 the actions that precede them, as action goals have a powerful influence on how infants
22 subsequently process observed actions (Henderson & Woodward, 2011). In the current study,
23 we compared event-related potential (ERP) responses, as described below, to sequential
24 actions that either did or did not cause a salient visual effect.

1 The ERP technique has made it possible to explore the neural mechanisms that support
2 action processing in infants. ERPs are voltage oscillations in the electroencephalography
3 (EEG) signal that are time-locked to the onset of perceived events (Luck, 2014). Components
4 can be identified in the ERP waveforms that mark specific stages of perceptual and cognitive
5 processes in infants (for a review, see de Haan, 2007). Two ERP components are particularly
6 relevant for research on infant action processing: the Negative central (Nc) and the N400,
7 which reflect visual attention and semantic processing, respectively (Kaduk et al., 2016; Pace
8 et al., 2013; Reid et al., 2009).

9 The Nc component has been interpreted as a marker of attention orientation towards
10 salient stimuli and is typically larger in response to novel or unexpected stimuli (for a review,
11 see Reynolds, 2015). The Nc emerges shortly after birth (Karrer & Monti, 1995), and between
12 3 to 6 months infants begin to show a stable Nc response that is larger for novel compared to
13 familiar stimuli (except in certain cases, such as a mother's face or emotionally salient
14 stimuli; (de Haan & Nelson, 1997). An increased negative amplitude is thought to reflect
15 increased allocation of attention towards the stimulus (Courchesne et al., 1981; Richards,
16 2003). The Nc manifests as a negative deflection in the ERP waveform at central and midline
17 electrodes, peaking between 250 and 750ms following stimulus onset (de Haan, 2007). The
18 neural generators of the Nc are presumed to be prefrontal and frontal regions related to
19 attention and memory systems, reflecting cortical allocation of attention resources (Reynolds
20 et al., 2010).

21 The N400 component is observed in both adults and infants during processing of
22 'meaningful' stimuli; that is, stimuli that grant access to semantic, or conceptual, knowledge
23 (e.g., Reid & Striano, 2008; van Elk et al., 2014, 2009). The N400 is characterized by a
24 negative peak with a parietal scalp distribution that is sensitive to semantic incongruence (for
25 a review, see (Kutas & Federmeier, 2011). N400 effects have been reported in infants as

1 young as 9 months of age, with a peak latency that is delayed relative to the adult component
2 (Kaduk et al., 2016; Parise & Csibra, 2012; Reid et al., 2009). By 14 months of age, N400
3 effects become more robust and are elicited in a broader range of modalities and conventional
4 paradigms (Friedrich & Friederici, 2005, 2004). Infants display an N400 response following
5 an action outcome that is strange within the semantic context, such as bringing a spoonful of
6 food to one's forehead and is thus thought to be functionally similar to the adult N400. N400
7 effects during action observation indicate a violation of an expected action outcome (Kaduk et
8 al., 2016; Reid et al., 2009).

9 The current experiment used ERPs to investigate learning during observation of action
10 sequences containing statistical regularities. Infants of 8-11 months of age experienced a
11 learning and test phase. The learning phase consisted of a continuous video of an action
12 sequence, featuring two deterministic pairs embedded within an otherwise random sequence.
13 At test, infants observed another sequence that included two novel 'deviant' pairs, which
14 should violate their predictions if they had successfully learned the pairs. If infants perceive
15 these deviants as violations of the expected sequential order, this should result in an enhanced
16 Nc response to the deviant, relative to the original pairs, due to increased attention following
17 the violation. We further hypothesized that these responses would be stronger for the pair
18 associated with the action-effect. Finally, sequence violations might also elicit an N400
19 response, which would indicate that statistical regularities could provide the contextual
20 information needed for storing semantic knowledge about the expected action sequence.

21 The current study implemented eye-tracking in addition to EEG measurements to
22 assess whether infants also made predictive eye movements towards upcoming actions prior
23 to their onset as the action sequence unfolded. Specifically, we examined whether infants
24 looked toward the second action of a pair—or the action effect, for the Effect pair—during the
25 first action of the pair. This measure provided a behavioral indicator of learning and extended

1 results from prior research with 18-month-old infants (Monroy et al., 2017). As an
2 exploratory measure, we related the eye-tracking to the EEG measures to further clarify the
3 neural correlates of learning.

4 In sum, our primary aim in the current study was to identify novel electrophysiological
5 evidence for statistical learning during observation of action sequences and identify whether
6 they relate to behavioral indicators of learning. Our second goal was to identify the presence
7 of ERP components associated with specific attention and/or semantic processes during action
8 observation.

9 **2.0 Method**

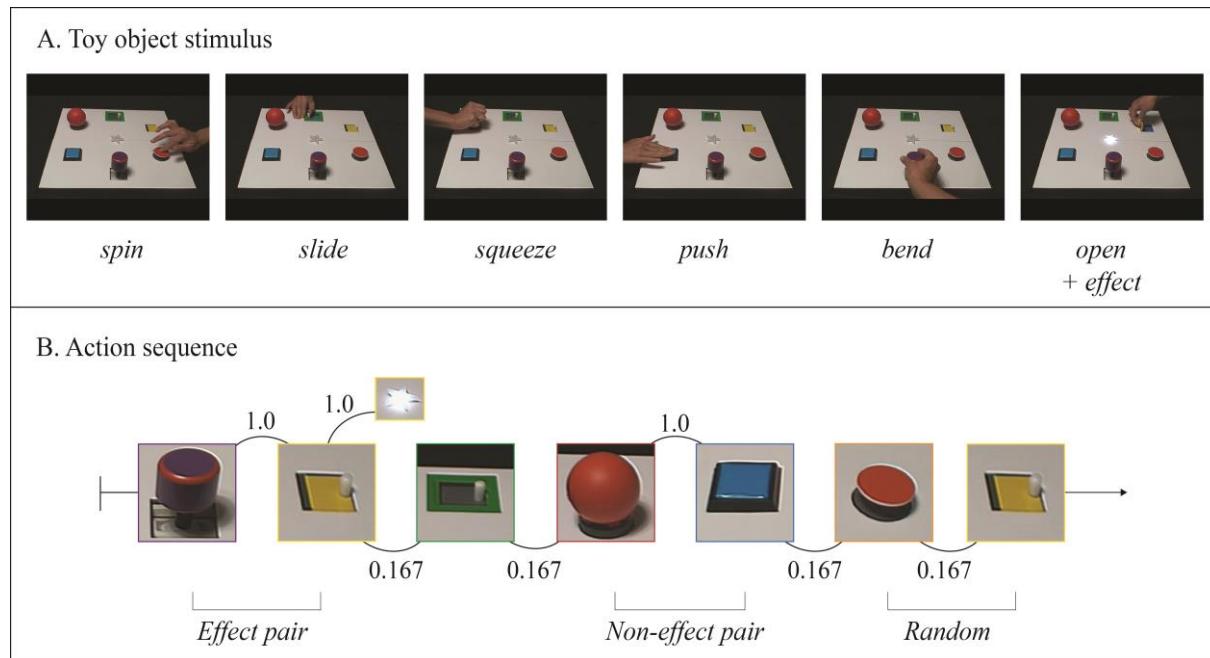
10 2.1 Participants

11 Fourteen infants were included in the final sample for the ERP analysis ($M = 10.9$
12 months, *range*: 8.9-11.9 months, 9 males). Of these, seven infants were included in the final
13 sample for the eye-tracking analysis ($M = 10.4$ months, *range*: 9.1-11.9 months, 3 males). An
14 additional 8 infants contributed complete datasets from eye-tracking but not EEG
15 measurements ($N = 15$, $M = 10.3$ months, *range*: 9.0-11.9 months, 6 males). All infants were
16 recruited from a database of families interested in participating in developmental research.
17 Although no demographic information was collected, the families were representative of the
18 population of the small European city in which the data was collected (i.e., largely Caucasian
19 and middle-class). Written informed consent was acquired from all parents, and families
20 received a thank-you gift of 10£ for participation. Fourteen additional infants were excluded
21 from the ERP analysis due to insufficient artifact-free trials (given a minimum criterion of
22 three trials per condition, $N = 9$) or excessive fussiness ($N = 5$). This attrition rate (50%) is
23 typical for EEG experiments with young infants (cf. Hoehl & Wahl, 2012; Meyer et al.,
24 2015). An additional eighteen infants visited the lab but were unable to participate in the
25 experiment due to equipment failure.

1 2.2 Stimuli

2 2.2.1 Learning Phase

3 Infants were first shown a video of an adult agent performing an action sequence with
 4 a novel toy, in which only the actor's hand was visible on screen (Figure 1). The toy featured
 5 six unique objects and a central star-shaped light. An action was defined as the manipulation
 6 of one object. Stimulus movies were filmed with a Sony HandyCam video camera and edited
 7 using Adobe Premiere Pro Cs5 software. All stimuli were presented on a screen with a
 8 resolution of 600 x 800 pixels, and a visual angle of 35 x 20 degrees.



10 Figure 1. A: Example frames depicting each action. B: Sequence structure and action

11 pairs. Numbers represent the transitional probabilities between actions. In (B) images are
 12 enlarged for clarity; infants actually observed the stimuli as in (A).

13

14 The sequence structure was defined according to the transitional probabilities between
 15 action steps. Two action pairs featured deterministic transitions (i.e. action 'A' followed
 16 action 'B' with 100% predictability), whereas transitions between unpaired actions had a
 17 0.167 (1/6) probability. One of the deterministic pairs caused a light to turn on during the

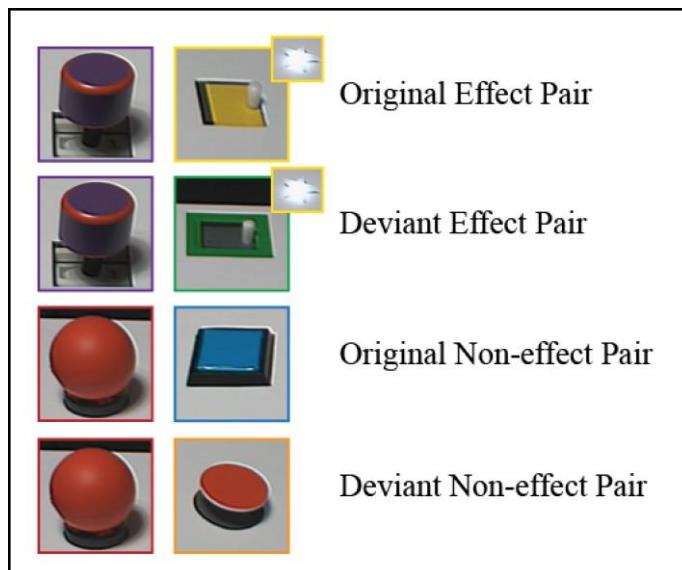
1 second action; the second pair did not cause any effect. We refer to these, respectively, as the
2 ‘Effect’ and ‘No-effect’ pairs. For both pairs, the second actions were defined as *target*
3 *actions*, as these were the events that became predictable during the unfolding of the
4 sequence. We constrained the sequence such that no action or pair occurred more than three
5 times consecutively, and such that all events occurred with equal frequency for a total of 12
6 repetitions of every action and pair. Importantly, target actions also occurred elsewhere in the
7 sequence outside of their pairs, to ensure that infants would need to learn the two-step pair
8 structure rather than only associating the effect with the target action. The actions that defined
9 the Effect and No-effect pairs were counterbalanced in two sets of videos, and infants were
10 randomly assigned to one stimuli set.

11 For each action, the actor’s hand entered the screen near the object, performed the
12 action, and exited the screen in the same place. A brief pause occurred between actions,
13 during which the object was viewed with no hand present. The onset of the light (effect)
14 occurred at a natural mid-point of the target action during the Effect pair and ended when the
15 action was completed. For example, during the target action ‘open’, the light went on the
16 moment the small yellow door was fully open, and went off again as the hand closed the door.

17 Each video was divided into four blocks of 24 actions (with approximately 3 trials of
18 each pair in each block) with the viewing angle oriented from a different side of the toy box in
19 each block to ensure that the object location on the screen did not become a predictable cue.
20 At the beginning of a block, one still frame of the object was presented with no hand visible to
21 help the infant reorient to the new perspective. In total, the entire learning phase lasted
22 approximately six minutes. Engaging, upbeat music was played throughout the entire
23 sequence that did not correspond in any way to the unfolding action sequence.

1 2.2.2 Test Phase

2 Still frames were selected from the videos that were representative of the mid-point of
 3 each action for the test phase. The test phase consisted of one block of 144 images, in which
 4 the target action of each pair was replaced on half of the trials by a different action. For
 5 example, if the Effect pair during the learning phase was *bend-open*, infants saw *bend-open*
 6 and *bend-slide*, with both target images *open* and *slide* featuring the effect (Figure 2).



7
 8 Figure 2: Test conditions: examples of the original and deviant action pairs (images enlarged
 9 for clarity; infants observed the display as they had seen it during the learning phase).

10

11 2.3 Procedure

12 Parents and infants were invited into the lab and first given the opportunity to become
 13 comfortable with the new surroundings. After the procedure was explained, parents provided
 14 written informed consent. Infants sat on their parent's lap throughout all phases of the study.
 15 After preparing the EEG net, parents were instructed to refrain from influencing their child
 16 during the experiment. The entire session was videotaped with the camera positioned behind
 17 and to the right of the presentation screen, with full view of the child and parent. Although we
 18 only analyzed the eye-tracking data from the learning phase, both EEG and eye-tracking data

1 were recorded throughout both phases of the experiment in order to avoid disrupting the
2 experiment and the eye-tracking calibration for the EEG preparation.

3 2.3.1 EEG Acquisition and Processing

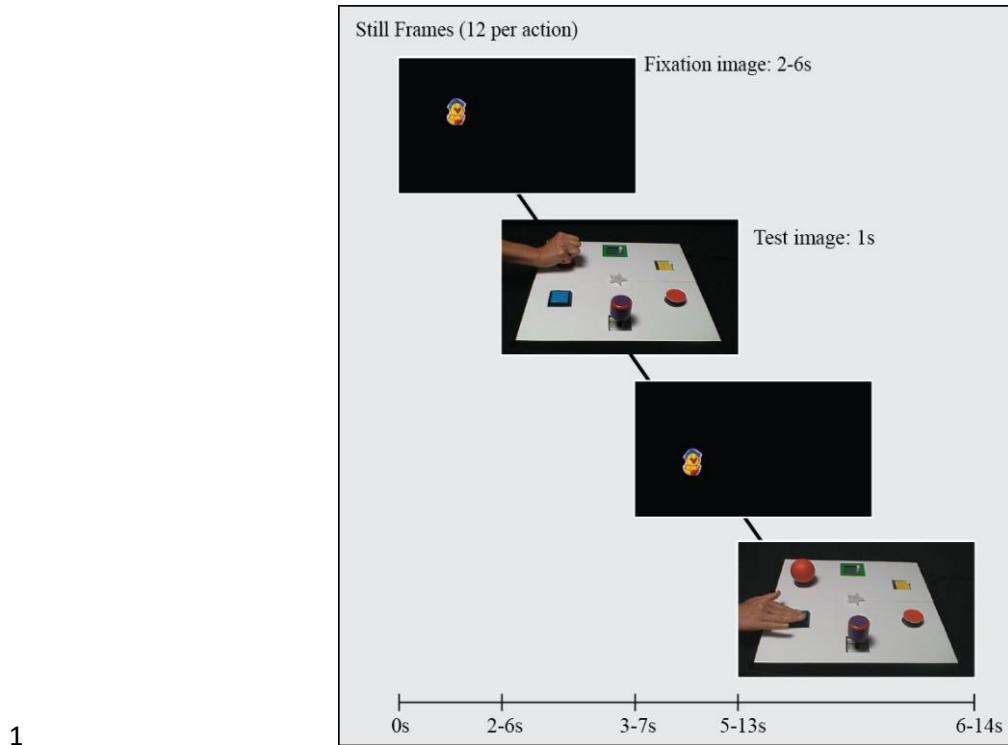
4 EEG was recorded continuously with the Electrical Geodesics Incorporated (Eugene,
5 Oregon, USA) 128-channel recording system (Net Station 4.1.1). The EEG signal was
6 referenced to the vertex and recorded with a 0.1-100 Hz band-pass filter and a sampling rate
7 of 500Hz. Data was preprocessed using Net Station 4.3 Waveform Tools. Recordings were
8 digitally filtered with a 0.3-Hz high-pass filter and a 30-Hz low-pass filter, and were
9 segmented from 200ms before to 1000ms after the stimulus onset (the test image) for each
10 trial. Segments were visually inspected to exclude EEG artifacts such as noisy channels and
11 artifacts caused by eye and body movements. Any segments in which infants were not
12 attending to the screen based on video recordings of the session were rejected. Participants
13 were required to have at least three artifact-free trials per experimental condition (Figure 2) to
14 be included in further analyses. This trial inclusion criterion was selected based on previous
15 evidence that reliable Nc and N400 effects with infants are found with as few as three to
16 seven trials per condition (Kaduk et al., 2013, 2016; Missana et al., 2014; Stets and Reid,
17 2011). The mean number of artifact-free EEG trials contributed by infants across conditions
18 was 6.27 (range = 3–11). For each condition, the mean number of trials contributed was as
19 follows: Deviant_{Effectpair} = 5.57 ($SD = 1.55$), Original_{Effectpair} = 6.07 ($SD = 2.53$),
20 Deviant_{Noneffectpair} = 6.43 ($SD = 2.1$), Original_{Noneffectpair} = 7.07 ($SD = 2.1$).

21 2.3.2 Eye-Tracking

22 Eye movements were recorded using a Tobii TX300 eye-tracker (Tobii, Stockholm,
23 Sweden) at 120Hz with a spatial filter of 40 pixels and a temporal filter of 100ms. First, a 5-
24 point calibration sequence was repeated until valid calibration data was acquired for at least
25 four points or a maximum of three attempts. Following calibration, infants watched the

1 learning video and then were immediately shown the test phase following a brief (<1s) pause
2 during which they observed a blank screen. During the test phase, the experimenter could
3 initiate attention-grabbers when the infant looked away from the stimuli, or a pause if the
4 infant became distressed. Attention-grabbers were only implemented during the test phase—
5 thus, the learning phase was never interrupted by them—and they could only be initiated
6 during a fixation image so as not to further disrupt the sequence. Following attention-
7 grabbers, the sequence resumed from where it had left off. Video stimuli were presented using
8 Psychtoolbox for Matlab and a custom-made application written using Python. Sounds were
9 played through external speakers.

10 During the test trials, infants were assigned to either a gaze-contingent or automatic
11 presentation group. This was due to the sample also being used for a separate, unrelated
12 methodological study (in the final ERP sample, there were 8 infants in the gaze-contingent
13 condition and 6 infants in the automatic condition). In both groups, each test trial began with a
14 fixation image presented at a size of 3° x 3.7° in the location of the upcoming action (Figure
15 3). We chose to present the fixation image in the target location in order to avoid eye
16 movements towards the target because eye movements could distort the EEG signal and
17 interfere with ERP components (Hoehl and Wahl, 2012). In the gaze-contingent condition, the
18 test image was immediately presented only if the infant was looking at the fixation image. If
19 the child was looking away, the fixation image would wiggle and play a jingling sound until
20 the infant looked at the target location, or for a maximum of 4s. Trial duration thus ranged
21 from 2s to a maximum of 6s. In the automatic condition, the fixation image remained for 1s
22 before the next image automatically appeared. Each trial thus lasted for a total fixed duration
23 of 2s. In both conditions, the test image was presented for an identical duration (1s); only the
24 duration of the fixation image varied.



2 Figure 3: Two example trials from the test phase.

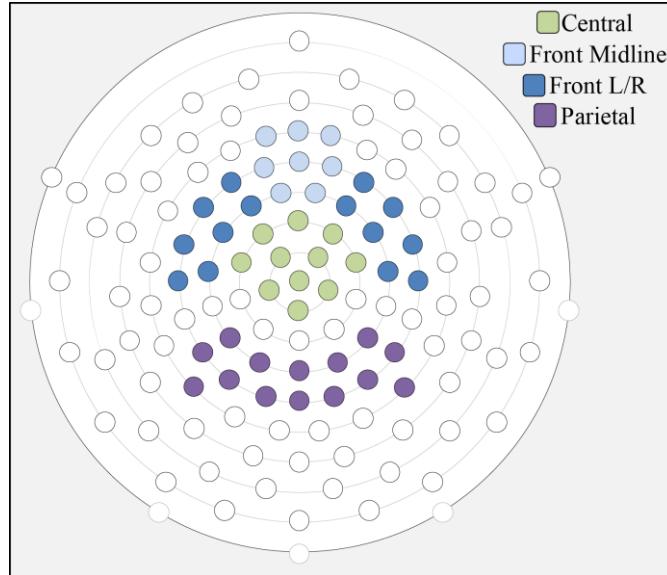
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4 3.0 Data Analysis

5 3.1 ERP Analysis: Test Phase

6 To identify the presence of an Nc component during the test trials, mean minimum
 7 amplitude of the ERP was calculated in selected channel groups (Figure 4) from 250-750ms
 8 post-stimulus, consistent with prior work on this component (Reid et al., 2009; Richards,
 9 2003). There is a lack of consistency among the infant studies that report an Nc effect; thus,
 10 we attempted to select a time window *a priori* that was consistent with most studies featuring
 11 a paradigm closest to our own. As the prefrontal cortex and anterior cingulate cortex have
 12 been suggested as the cortical source of the Nc, we expected to find a widespread frontal and
 13 central topography in our participant group (Reynolds & Richards, 2005). We confirmed our
 14 time window and channel group selection by visual inspection of the grand average
 15 waveforms. Mean amplitude was analyzed via a 2 (Pair: Effect, No-effect) x 2 (Condition:
 16 Deviant, Original) x 4 (Channel Location: Central, Frontal Midline, Frontal Left, Frontal

1 Right) ANOVA. Interactions were followed up with pairwise comparisons of estimated
 2 marginal means.



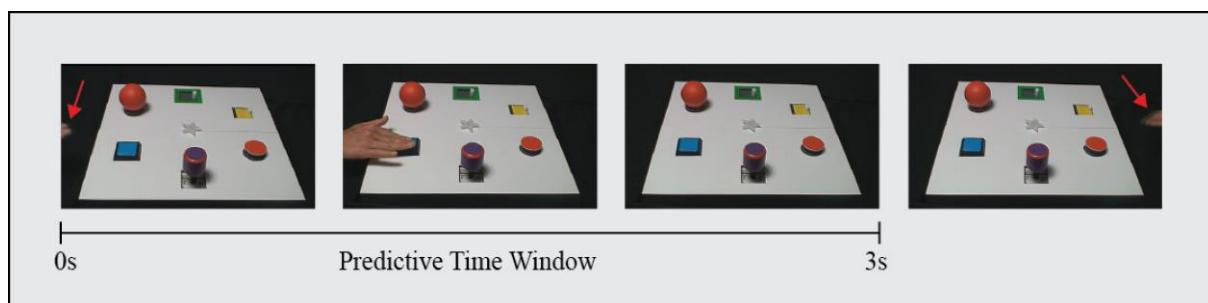
3
 4 Figure 4: An illustration of the EGI 128-channel groups selected for the ERP analysis. Central
 5 and frontal channel groups (blue and green) were selected for the Nc analysis; parietal
 6 channels (purple) were selected for the N400 analysis.
 7

8 For identification of the N400 component, we selected *a priori* the procedure outlined
 9 by Reid and colleagues (2009) that suggests a time-window analysis as a more appropriate
 10 statistical method when there is a defined peak in one condition but not the other. This method
 11 analyzes the variation in ERP amplitude across time-window samples between conditions and
 12 reveals the ERP effect of interest as an interaction between condition and time (for full
 13 details, see Hoormann et al., 1998). Though the N400 has a broader topography in adults, in
 14 infants it has been only observed in parietal regions most likely due to masking by the Nc
 15 component (Reid et al., 2009). For our analysis, we selected a time window from 500-700
 16 after stimulus onset in parietal channels, as suggested in Reid et al. (2009). After normalizing
 17 the data as suggested in Hoormann et al. (1998), variance of the ERP amplitude was analyzed

1 using a 2 (Pair: Effect, No-effect) x 2 (Condition: Deviant, Original) x 17 (Time: one sample
 2 per 12ms) ANOVA.

3 3.2 Eye Tracking Data: Learning Phase

4 Eye movement data from the learning phase were analyzed to assess anticipatory gaze
 5 fixations to upcoming target actions during predictive time windows. These were defined as
 6 the frame when the agent's hand appeared in order to perform the first action of a
 7 deterministic pair until immediately before it reappeared for the target action (Figure 5). This
 8 corresponds to the time in which the observer has enough information about what the next
 9 action will be to make a prediction about the upcoming location before the subsequent action
 10 occurs (Monroy et al., 2017). For both action pairs, we excluded the first trial for each pair, as
 11 infants should not be able to make a prediction based on prior information during the first
 12 trial. Thus, 11 trials were included in the final analysis for each deterministic pair. Infants
 13 observed an average of 6.5 ($SEM = 0.63$) repetitions of the Effect pair and 6.08 ($SEM = 0.64$)
 14 repetitions of the No-effect pair during the learning phase. We did not apply an inclusion
 15 criterion for the test phase based on looking time from the learning phase.



17 Figure 5: Example frames illustrating the predictive time window during the learning videos.
 18 Red arrows indicate the first frame in which the agent's hand appears.

19
 20 Regions of interest (ROI) of equal size were defined around each stimulus object.
 21 Fixations to the ROI of the target action during the predictive time window were counted as
 22 correct, and fixations to any other ROI were incorrect. Fixations to the object currently being

1 manipulated were excluded from calculations. For the Effect pair, fixations to the star were
 2 counted as correct; for the No-effect pair, they were excluded (Eqs. 1-4).

3 If infants learned the pair associations, they should look more to the target object of
 4 each pair than to all other objects during the first action. For each pair, we calculated the
 5 proportion of correct or incorrect fixations, out of the sum of all fixations within predictive
 6 time windows. For incorrect fixations, we summed the total fixations to the four alternative
 7 locations and divided by four to yield the average number of fixations to an incorrect region.

8 Effect Pair:

$$9 \quad \text{Correct} = \frac{\# \text{fixations to target \& effect}}{\text{total } \# \text{fixations to all objects \& effect}} \quad (1)$$

$$10 \quad \text{Incorrect} = \frac{\# \text{fixations to other 4 objects/4}}{\text{total } \# \text{fixations to all objects \& effect}} \quad (2)$$

11 No-effect Pair:

$$12 \quad \text{Correct} = \frac{\# \text{fixations to target}}{\text{total } \# \text{fixations to all objects}} \quad (3)$$

$$13 \quad \text{Incorrect} = \frac{\# \text{fixations to other 4 objects/4}}{\text{total } \# \text{fixations to all objects}} \quad (4)$$

14 Equations 1-4. Calculations of the proportion measures. For the effect pair, the effect ROI was
 15 included for the number of correct looks and the total number of looks ('all ROIs') while for
 16 the No-effect pair it was not included in the total number ('all objects').

17

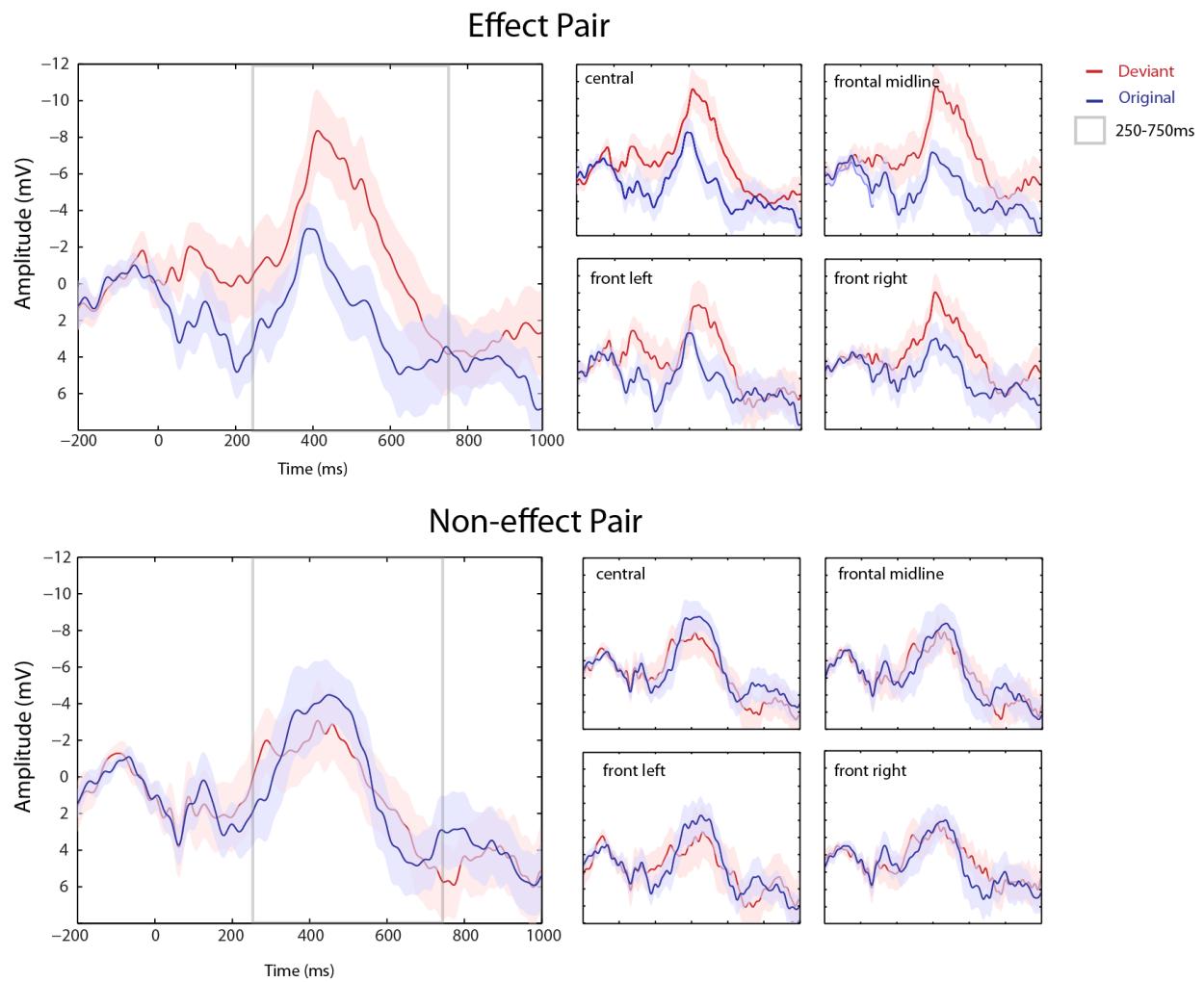
18 4.0 Results

19 4.1 Event-related potentials

20 4.1.1 Negative central

21 The Nc component was found as a clear negative peak located in frontal and central
 22 electrodes, peaking at approximately 400ms following stimulus onset (Figure 6). Latency and
 23 amplitude of the peak were analyzed separately. No significant effects were found for Nc
 24 latency, indicating that the ERP peak amplitude featured a similar time course across

1 conditions and pairs. For peak amplitude, the ANOVA analysis revealed a significant
 2 interaction between Pair and Condition, $F(1, 13) = 7.09, p = .02, \eta_p^2 = .35$. For the Effect pair,
 3 Nc amplitude was significantly greater following the deviant compared to the original targets
 4 (*mean difference* = $4.23\mu\text{V}$, $SE = 1.26, p = .005$). For the No-effect pair, no differences were
 5 found between deviant and original targets (*mean difference* = $-0.47\mu\text{V}, SE = 1.57$). As can be
 6 seen in Figure 6 (top), the response elicited by deviants of the Effect pair featured a clear peak
 7 that was more negative in amplitude relative to original actions; this pattern does not vary
 8 across frontal and central electrodes.



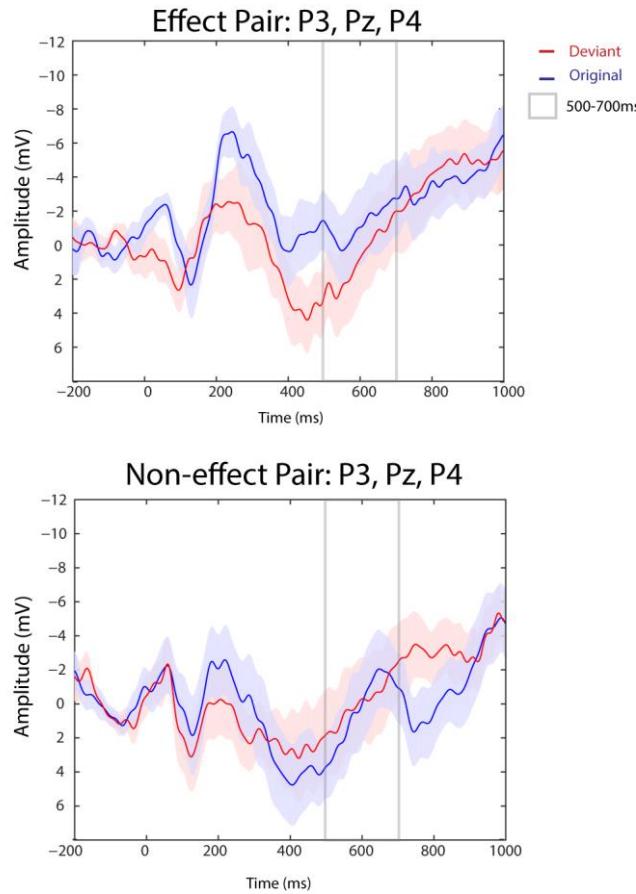
9
 10 Figure 6: The grand average event-related potential (ERP) waveforms over frontal and central
 11 channels. The larger plots (left) display the average across all channel groups selected for
 12 analysis. Gray rectangles indicate the time window of analysis for the Nc component (250-

1 750ms). The smaller plots (right) display the waveforms for each of the four channel groups
2 (see Figure 4). Shaded regions indicate standard errors. Negative is plotted up.

3
4 Data were collapsed across the automatic and gaze-contingent groups. To verify there
5 were no differences in the Nc amplitude because of stimulus presentation during the test
6 phase, the ANOVA was repeated with Presentation (Gaze-contingent vs. Automatic) as a
7 between-subjects factor. There were no significant main effects or interactions with
8 Presentation ($p > .24$) confirming that the Nc amplitude during experimental trials of interest
9 were not different between infants who observed gaze-contingent and automatic conditions.

10 4.1.2 N400

11 We found no clear evidence for an N400 effect in the grand averaged waveforms
12 based on either statistical analyses or visual inspection of the expected channel region (Figure
13 7). During the time window of interest, there was no interaction effect between Pair,
14 Condition, and Time ($p = .37$), confirming that the variation in ERP amplitude across time
15 window samples did not differ between conditions and this was consistent across pairs. There
16 were no other interaction effects with time or condition ($p > 0.27$). To confirm this null
17 finding, we also repeated this analysis using the standard technique commonly reported in the
18 adult literature. We extracted the mean amplitude during the time window of interest (500-
19 700ms) over the same channel groups and performed a 2 (Condition: Deviant, Original) x 3
20 (Channel: Pz, P3, P4) ANOVA, that also indicated no main effects or interactions with
21 Condition ($p > .25$).



1

2 *Figure 7.* The grand average event-related potential (ERP) waveforms over parietal channels.

3 The larger plots (left) display the average across all electrodes selected for analysis. Gray

4 rectangles indicate the time window of analysis for the N400 component (500-700ms).

5 Shaded regions indicate standard errors. Negative is plotted up.

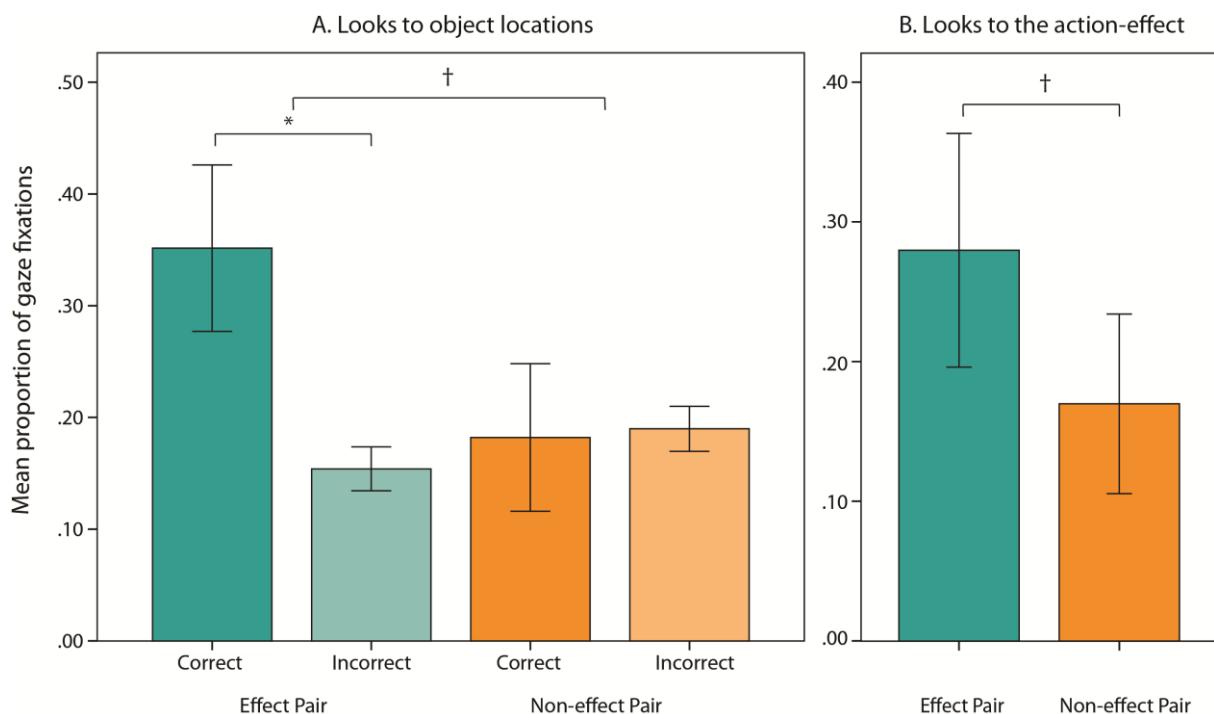
6

7 4.2 Eye Tracking Results: Learning Phase

8 Data were collapsed across the automatic and gaze-contingent groups, as there were no
9 differences in the stimulus presentation between these groups during the learning phase.

10 Across pairs, predictive fixations accounted for 60.22% of all gaze fixations and the
11 remaining 39.78% were fixations to the action currently occurring on screen. There were no
12 significant differences between the mean percentage of predictive looks for the Effect and No-
13 effect pairs ($p = .88$). A 2 (Pair: Effect, No-effect) x 2 (Location: Correct, Incorrect) ANOVA

1 yielded a marginal interaction effect between Location and Pair, $F(1, 14) = 3.34, p = .09, \eta_p^2$
 2 = .19. As can be seen in Figure 8A, this effect was due to a greater proportion of correct
 3 relative to incorrect fixations for the Effect pair (*mean difference* = .18, *SE* = .08; $p = .05$),
 4 and no difference for the No-effect pair (*mean difference* = -.02, *SE* = .03, $p = .51$). A *t*-test
 5 comparing fixations to the effect alone during Effect and No-effect pairs revealed a
 6 marginally significant difference between pairs ($t(14) = 1.75, p = .10$), suggesting that gaze
 7 fixations to the effect itself were more frequent during the first action of the Effect pair
 8 compared with the No-effect pair (Figure 8B).



9
 10 *Figure 8. A:* Proportions of fixations as a function of ROI and pair. *B:* Proportion of fixations
 11 to the action-effect location during the first action of each pair. Bars represent standard errors.
 12 † $p < .10$; * $p < .05$.

13

14 4.3 Relating Behavioral and Neural measures

15 In order to test for consistency between behavioral and ERP measures, we explored
 16 whether infants who demonstrated higher rates of correct predictions during the learning

1 phase were also those who demonstrated a robust Nc effect at test. Using a method similar to
2 Reynolds et al. (2010), infants who contributed both eye-tracking and EEG data
3 measurements ($N = 7$) were divided into two groups based on the mean amplitude difference
4 between conditions across all electrodes. Infants with an Nc difference greater than the group
5 mean (-4.23mV; $N = 5$) received a score of 1 and infants below the mean ($N = 2$) were
6 assigned a 0. We then conducted an ANOVA analysis of gaze fixations as before, with Nc
7 Difference (above or below mean) as an additional between-subjects factor. This revealed a
8 main effect of Nc Difference, $F(1, 5) = 9.53, p = .03, \eta_p^2 = .66$. Infants who had a larger Nc
9 effect also made a greater proportion of correct relative to incorrect fixations (*mean difference*
10 = .27, *SE* = .07, $p = .01$) than those infants with a weaker Nc effect (*mean difference* = .01, *SE*
11 = .11, $p = .93$).

12 5.0 Discussion

13 The central aim of this study was to investigate the ERP components associated with
14 violations of prediction based on the statistical structure in action sequences. Specifically, we
15 asked whether deviant action events, which violated a previously learned association, altered
16 infants' ERP responses. We tested for the presence of two potential components, the Nc and
17 N400, which are known to index perceptual and semantic cognitive responses, respectively.
18 Second, during the learning phase of the experiment, we investigated whether infants made
19 predictive eye movements to upcoming actions.

20 5.1 Nc Findings and Interpretation

21 To investigate the response to a violation of predictions built up on the basis of
22 statistical learning, we examined the ERP responses following deviant actions that were
23 inconsistent with previously learned sequential regularities. Our results illustrate an enhanced
24 Nc component in response to deviant action pairs, relative to original action pairs, when they
25 were associated with a salient effect. Prior studies have found an Nc effect for repeated

1 observations of single action events, such as bringing a spoon to the mouth (Kaduk et al.,
2 2016; Reid et al., 2009). Our study extends these prior findings, by showing that an Nc effect
3 can occur for individual action steps occurring within longer sequences, and is modulated by
4 their congruency within the learned sequential structure.

5 The topographical distribution of the Nc component we observed is consistent with
6 previous findings (Reynolds & Richards, 2009, 2005). Reynolds and colleagues (2005)
7 showed that the Nc is greater during periods of sustained attention and is likely to reflect
8 activity from distinct brain areas involved in information processing that are independently
9 influenced by attentional state. Likely cortical sources of the infant Nc include the inferior and
10 superior prefrontal cortex and the anterior cingulate cortex, which are neural regions that
11 modulate sustained attention and recognition memory (for a review, see Duncan & Owen,
12 2000). This suggest that the deviant targets in our paradigm triggered additional visual
13 processing, indicating that this attention system was modulated by changes in the rules
14 governing the sequential structure. There are two interpretations for explaining the presence
15 of the Nc component in our study. The first interpretation, supported by our eye-tracking
16 results, is that infants encoded the predictive relation between the actions of the effect pair
17 during the learning phase and perceived the deviant pair as surprising or unexpected. In other
18 words, the Nc effect that we observed may reflect the recognition of a violation of perceptual
19 predictions for how the following events should unfold.

20 A second interpretation of our findings for the Nc component is that infants
21 recognized the association between the deviant second action and the effect, rather than
22 surprise at observing this event contingent upon the first action of the pair. In our study,
23 deviant items were both statistically unlikely and visual novelties. Future research aimed at
24 dissociating the separate contributions of stimulus novelty and probability could clarify
25 whether the Nc response reflects the buildup of stored information about stimulus probability

1 or whether it is limited to the detection of familiar versus novel items. However, infants
2 seemed to make correct visual predictions only for the Effect pair, an indication that learning
3 may have only occurred when there was an upcoming salient effect. This finding, coupled
4 with its relation to the strength of the observed Nc effect, suggests that visual novelty alone is
5 not sufficient to explain our pattern of findings.

6 Though both deviant Effect and No-effect events violated the action sequence, only
7 the deviant event co-occurring with the effect elicited the enhanced Nc peak. Previous
8 research has shown that action-effects influence infants' learning and imitation as measured in
9 their behavioral responses (Hauf & Aschersleben, 2008; Verschoor et al., 2010). One
10 explanation provided in the literature is that bidirectional action-effect associations can be
11 established through observation, which results in motor representations of the effects
12 themselves. From this perspective, the effect may have resulted in a corresponding
13 representation of the action 'unit' (i.e., the two-step pair) preceding it, which infants did not
14 acquire for the No-effect pair. A second explanation is that action-effects are salient
15 perceptual cues that make the structure easier for infants to attend to and maintain in working
16 memory. Accordingly, several prior studies have provided evidence that the influence of
17 action-effects on infant behavior is due to a bias towards perceiving actions in terms of their
18 goal structure (Buresh & Woodward, 2007; Cannon & Woodward, 2012; Klein et al., 2006).
19 In line with this notion, it is possible that the effect was perceived as a goal or intentional
20 outcome of the activity stream, and thus biased attention toward that particular action pair
21 because of its temporal relation with the effect. A third possible explanation, drawn from the
22 literature on reinforcement learning, is that the action-effect was perceived as a rewarding
23 sensory change in the environment. Evidence from adult studies suggests that external
24 rewards are crucial for observers to update their internal representations of the environment
25 (Gläscher et al., 2010). Infants might have selectively updated their model of the action

1 sequence only when observing a perceptible external reward, provided by the light turning on.
2 Whether observing the light was rewarding to the infants or perceived as a potential reward or
3 goal of the actor is a novel question that could be empirically tested.

4 Our findings are consistent with a large body of literature examining the development
5 of causal learning, which explains how children achieve increasingly sophisticated theories
6 about the social and physical world from noisy and limited data (see for a review, Gopnik &
7 Wellman, 2012). This work has shown that Bayesian concepts of inference can also apply to
8 children's learning of the causal structure of the world. Bayesian inference refers to the
9 process of combining prior evidence with current incoming data and forming a prediction
10 about what will occur next, resulting in a probabilistic model of the world. Of relevance for
11 the current study, probabilistic models also provide one of the most elegant explanations for
12 how the motor system can predict the actions of other people (Kilner, 2011). Our data show
13 that, at 10 months of age, infants can use statistical information from observation alone to
14 generate expectations about the actions and their effects. This step may reflect the initial
15 building of prior knowledge about the most likely outcome of an action, a necessary
16 prerequisite for constructing causal models of other people's actions and their social
17 intentions.

18 5.2 The N400 Component

19 Prior studies have shown that unexpected final outcomes of familiar action sequences,
20 such as bringing a pretzel to one's ear or a spoon with food to one's forehead, elicits an N400
21 effect in both infants and adults (Reid et al., 2009, Kaduk et al., 2016). Across studies, N400
22 effects become smaller as stimulus probability increases. This explanation proposed in the
23 literature is that processing incoming information is facilitated when it 'fits' with the current
24 context, if accumulated experience from previous contexts has built up meaning (Kutas &
25 Federmeier, 2011). From this perspective, an N400 response to action stimuli is interpreted as

1 a violation of predictions that are based on current semantic information and prior
2 experiences.

3 In the current experiment, we found no evidence for an N400 response to deviant
4 action steps. Unlike prior studies, which have shown N400 effects for action events that occur
5 within a familiar context ('day-to-day' actions such as eating), our study featured novel action
6 sequences which were also abstract, in the sense that they did not reach an overarching goal or
7 take place in a familiar setting. Thus, the statistical structure was the only information infants
8 could use to build expectations about the sequence, which required them to retain six different
9 objects and the transitional probabilities between them in memory. One simple explanation is
10 that the brief learning phase was not sufficient for young infants to build up a semantic
11 context for the observed action events. Perhaps infants need to sample extensive amounts of
12 data to build up a context in which to compare new incoming information. Another possibility
13 is that actions and their context need to become associated with a goal that the observer has
14 experience with, before they engage the cognitive systems associated with semantics and
15 conceptual knowledge. The factors that cause a shift from perceptual to semantic processing
16 in action sequences during development are an intriguing question for further research.

17 5.3 Predictive gaze fixations

18 Infants made more predictive gaze fixations to the correct upcoming events than to
19 other object locations during the learning phase of the experiment. This finding provides
20 evidence they detected the pair structure of the unfolding action sequence, and used this
21 information to guide their looking behavior. Critically, this behavior was modulated by
22 whether or not a predictable action event was associated with a salient effect. Correct
23 anticipations were more frequent for the Effect pair than the No-effect pair, and anticipations
24 to the effect itself during predictive time windows were also marginally higher for Effect pairs
25 than the No-effect pair. This finding is partially consistent with a prior experiment in which

1 18-month-old infants only demonstrated spontaneous, uninstructed imitation of actions that
2 resulted in action-effects, and not of actions without a corresponding effect (Monroy et al.,
3 2017). In that study, the older infants also only demonstrated a relation between their visual
4 anticipations during observation and their ability to imitate upcoming actions for actions that
5 caused effects. These findings, taken together with the current study, suggest that action-
6 effects provide a learning cue that guides infant behaviors during both action perception and
7 action control. Further, Monroy et al. (2017) also found that the 18-month-olds were able
8 learn both pair types, even in the absence of an action-effect, which may point to interesting
9 developmental changes in sensitivity to effect-related cues occurring between the first and
10 second year of life.

11 The eye-tracking data yielded marginally significant differences between experimental
12 conditions, which may have been due to the small number of infants who yielded enough data
13 for analysis. Alternatively, the task demands of our experiment were relatively high: infants
14 needed to continuously attend to the screen, remember and encode the pair structure in the
15 unfolding sequence, and make predictive eye movements towards one of many possible
16 locations on the screen within a brief time period. Prior research has shown that under
17 conditions of uncertainty, even adults make fewer predictive movements—which require
18 effort and are therefore costly—and will prefer to assume a neutral position (Dale et al.,
19 2012). It is possible that our learning effects are small because infants at this age are just
20 beginning to acquire the ability to encode the statistical relations in more complex stimuli, or
21 that they do not always make visual predictions during ongoing observation. Future research
22 could aim to differentiate these two possibilities. Despite this, the consistency between our
23 eye-tracking and ERP results provides converging evidence that infants learned to predict the
24 outcome of the sequence structure for the Effect pair.

1 5.4 Relation between behavioral and ERP measures

2 Our method for assessing the relation between behavioral and neural measures of
3 learning was to examine infants' predictive gaze fixations during the learning phase in
4 relation to the magnitude of their Nc response during test trials. In a study aimed at
5 identifying the relation between infant visual preferences and ERP responses, Reynolds and
6 colleagues (Reynolds & Richards, 2005; 2009) provided evidence that infants aged 4.5-7.5
7 months who demonstrated a visual preference for novel events were those that showed an Nc
8 effect with greater amplitude. Consistent with these findings, in our study, the infants who
9 demonstrated a greater Nc amplitude in response to a deviant target action in the action-effect
10 condition also made a greater proportion of correct, relative to incorrect, predictive gaze
11 fixations in this condition. This result suggests that the Nc response may reflect predictive
12 processes based on the perception statistical regularities, which adds to the current
13 understanding of the functional significance of the Nc in young infants.

14 The sample size in the current study was limited due to difficulties in combining EEG
15 and eye-tracking data collection methodologies with young infants, which is typical for
16 developmental research and is consistent with similar studies (for a meta-analysis see Stets et
17 al., 2012). Due to the combination of a small sample size and limited number of trials in our
18 experimental conditions, findings from the current study should be interpreted cautiously and
19 validated in future work. However, we also note that our main finding—the observed Nc
20 component—is consistent with a large body of prior studies (reviewed in de Haan, 2007).
21 Specifically, the Nc component in the current study matches previously reported findings both
22 in terms of the experimental context in which it was elicited—that is, it reflects a response to
23 a perceptually unexpected event—and also its characteristics such as latency and morphology
24 of the waveform.

1 5.5 Conclusion

2 Human action naturally contains statistical regularities that define the overall
3 predictability of upcoming action events. The ability to recruit perceptual processes for
4 detecting these regularities is critical for making accurate predictions during action
5 observation. The results of this experiment suggest that, by ten months of age, infants are
6 sensitive to the sequential structure between action steps when they result in salient effects.
7 Our study further supports a consistency between neural and behavioral measures of statistical
8 learning in infancy. In sum, statistical regularities provide a learning cue that guides visual
9 expectations and attention during ongoing processing of novel action sequences. The findings
10 reported here have direct implications for our understanding of the development of social
11 cognition in infancy. We suggest that infants initially rely on their powerful statistical
12 learning skills to detect regularities among the actions of other people, enabling them to
13 anticipate upcoming action goals and to eventually attain understanding of the mental states of
14 other people.

15 **Acknowledgements**

16 We thank Dr. Eugenio Parise for valuable feedback and discussions, Uschi Mason for help
17 recruiting infant participants, Philip van den Broek for programming support with the eye-
18 tracking data analysis, Barrie Usherwood for invaluable technical support in the lab, the
19 members of the Lancaster Babylab for graciously hosting the primary author during her time
20 as a visiting student, as well as the BabyBRAIN lab in Nijmegen for constructive feedback
21 and support during the data analysis.

22

23 Funding: This work was supported by an Initial Training Network (ITN) of the People Marie
24 Curie Actions—Seventh Research Programme (FP7) of the European Union (grant number
25 FP7ITN2011-289404).

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